V. KOLESNIKOV

THE ROOT SYSTEM OF FRUIT PLANTS

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THE ROOT SYSTEM OF FRUIT PLANTS

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FROM THE AUTHOR

There has hitherto been no work on horticulture in any language devoted to the various techniques of studying the root systems of fruit plants, but the gap has now been largely filled by the second, revised and considerably expanded edition of this book.

The *Root System of Fruit Plants* provides the horticulturist with the information he needs to be able to choose an adequate method for discovering the causes of weak growth in fruit-bearing plants, for determining the correct depth of soil treatment in orchards and soft-fruit plantations, and for improving the system of agrotechnical measures that will ensure high yields of fruit.

A knowledge of the techniques of studying root systems is also essential for those engaged in laying out orchards in new areas, in order to determine the precise depth of preplanting ploughing and the planting distances for trees and shrubs in various soils.

Many of these techniques can be employed in studying the root systems of forest trees, decoratives, and grapevines, and some are also applicable for the examination of vegetables and field crops.

The book is recommended for research workers, teachers, post-graduate students, and undergraduates of agricultural faculties and colleges, and for practising agronomists.

V. Kolesnikov

CHAPTER 1

STRUCTURE AND ACTIVITY OF THE ROOT SYSTEM

Fruit plants have gone through extremely long evolutionary development. Their hereditary nature has been forming throughout the centuries, changing and adapting itself to the environment. New characters became inborn and then were passed on to new generations. As a result the root and above-ground systems of different plants acquired their specific appearance, structure, and size and developed each its own relationship and interdependence with the environmental conditions.

There are about 50 species of fruit plants in the Soviet Union. They are grouped as follows in accordance with their morphological characters and size:

(1) *trees of prominent height with a clearly defined stem* (pecan, walnut, sweet chestnut, pear, and sweet cherry);

(2) *trees of lesser height with a less defined stem* (apple, apricot, mountain ash, persimmon, and the tree-like varieties of plum and sour cherry);

(3) *shrub-like trees* (shrub-like varieties of sour cherry and plum, peach, filbert, pomegranate, fig, Cornelian cherry);

(4) *shrubs* (gooseberry and the currants, raspberry and blackberry);

(5) *liana*, or *climbing plants* (actinidia and magnolia vine);

(6) *herbaceous plants* (strawberry and cranberry).

Fruit plants vary widely in height: from a few centimetres (strawberry) to 1-3 metres (the shrubs) and 20 metres and higher (tree varieties). They also vary in longevity. For instance, under most favourable natural conditions the olive and the sweet chestnut live up to 1,000 years, the walnut, 100-300 years, the apple and the pear,

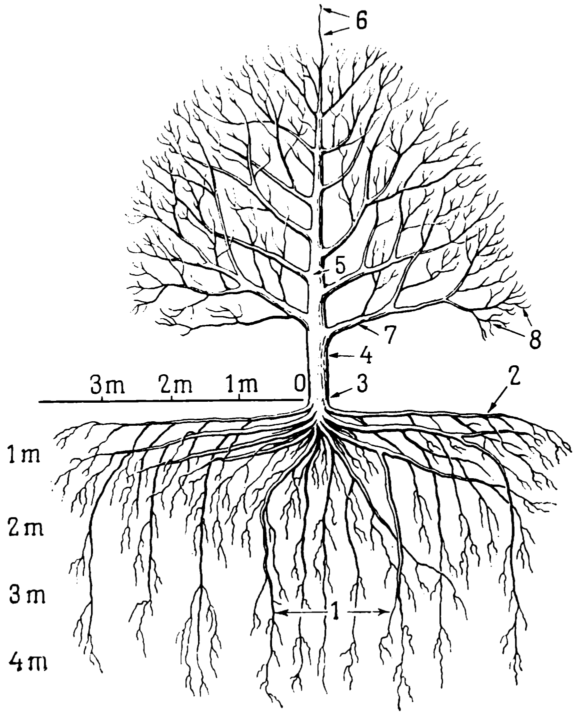


Fig. 1. Main parts of a fruit tree:
1—vertical roots; *2*—horizontal roots; *3*—root collar; *4*—trunk; *5*—stem; *6*—central leader; *7*—main branches; *8*—laterals

50-100 years, the sweet cherry and the apricot, 30-50 years, the plum and the peach, 20-30 years; the currants and other shrubs have a still shorter lifetime.

Fruit plants have three main vegetative organs: the *roots*, the *stem* (or *trunk*), and the *leaves*. All other parts of the plant—branches, buds, flowers, etc.—result from metamorphoses of the main organs (see Fig. 1).

The Role of the Root System and the History of Its Study

The scientists and growers have long been interested in the structure and activity of the root system of plants, but detailed and systematic studies were begun only quite re-

cently. Previous research had mostly been concerned with the above-ground parts of a plant.

Even at the early stages of research it occurred to scientists that the control of plant growth and fruit bearing would be more successful with equally good knowledge of the structure and activity of both the above-ground and underground systems, and of their interrelation throughout their ontogenetic development. This was convincingly confirmed afterwards.

Herbaceous, decorative and forest plants were studied first, and then orchard trees and shrubs. More than two centuries ago the root system of herbaceous and forest plants was described by Hales (1727), and then studied by Du Hamel du Monceau (1758), Bobrinsky (1852), Sachs (1865), Slyozkin (1893), Deherain (1893) and other scientists. The root system of fruit plants was studied by Bailey (1895), Goff (1897), Shitt (1913), and others.

A great contribution to the investigation of the root system was made by Cannon (1911), Modestov (1916), Miller (1916) and Weaver (1926). Later on large-scale experiments were conducted in the USSR and other countries, particularly in the USA, Japan, England, Germany, Italy, Hungary, and Roumania. At the same time methods for studying the root system of fruit plants were developed.

During the last fifty years or so the basic functions of roots have been defined more comprehensively and convincingly than during the preceding centuries.

Experiments conducted by Pryanishnikov (1895) and Kossovich (1902) showed that ammonia and nitrates are the main sources of nitrogen for all plants and are equally assimilable under optimum conditions of reaction (pH value) and with sufficient carbohydrate supply. Reduction of nitrates to ammonia starts directly in the root system. The ammonia nitrogen supplied to the plant is not stored up in the tissues but is used, in particular, to build up amino acids and amides, with carbohydrates and asparagine (an organic nitrogenous compound) always taking part in the process.

Votchal (1916) discovered amylase and certain other enzymes in the bleeding sap of trees. Later Bykov (1929), in studying bleeding sap, arrived at the conclusion that the substances absorbed from the soil are combined in the root

system, accumulating there temporarily in the form of some compounds or other. Thus the root system takes a more active part in plant nutrition than was believed before. Potapov (1936) established that a considerable percentage of nitrogen found in bleeding sap occurs in the form of organic compounds, including amides. Therefore one of the most important processes of secondary synthesis described earlier by Pryanishnikov in his works on nitrogen metabolism takes place in the cells of the absorbing zone of the root system. Some other convincing evidence of the active role of the root system in nitrogen metabolism has been obtained. Shmuk, Smirnov and Ilyin (1941) and Ilyin (1948) found that the leaves of a tobacco plant grafted on a tomato plant contained no nicotine, but if a cutting was taken from the tobacco scion and rooted, then nicotine began to accumulate in the leaves of the cutting. On the other hand, the leaves of a tomato plant grafted on tobacco contained up to 4 per cent nicotine.

Organic compounds are synthesized in the root system from the absorbed non-organic nitrogenous compounds, the process being specific for each given plant variety (Sabinin, 1955). It was found from studies of nitrogen metabolism in fruit plants that the active roots of apple trees largely control the initial stages of the synthesis of organic nitrogen and that the reduction of nitrates in peach trees occurs almost entirely in the roots. Analyses made in experimental conditions did not reveal any perceptible amounts of inorganic nitrogen in the above-ground tissues of apple trees, elders and poplars. In one-year-old apple seedlings grown in jars containing water and sand protein synthesis took place in the active roots supplied with nitrogen; proteins accumulated only there and their concentration was considerably higher than in the roots of other plant seedlings grown in a nutrient solution devoid of nitrogens. With a rise in the temperature to 21.1°C most of the newly synthesized amino acids and asparagine moved up from the active roots to the buds, which blossomed at a higher temperature. In peach trees the uptake of nitrogen by the roots occurred at temperatures above freezing point, but the absorbed nitrogen was not detected in the above-ground parts at air temperatures below +7.2°C. Marked absorption of nitrogen of nitrates and ammonium salts and its conversion into organic forms were observed in the roots of apple trees in the

period of their rest at low temperatures from 0° to 0.6°C. (Thomas, 1927; Eckerson, 1931; Blake, 1933; Nightingale, 1935; Davidson and Shieve, 1934; Loomis, 1935; Williams, Batjer, Magness and Regeimbal, 1940, and others.)

The root system of *Taraxacum hybernum*, a rubber-producing plant, is capable of synthesizing rubber from the photosynthesis products arriving from burdock leaves (Prokofyev, 1949). The source of resin and rubber synthesis in the root system can be non-specific products of photosynthesis flowing from the leaves (Zhdanova, 1954). Various amino acids are formed in the roots and then conveyed to the leaves (Kursanov, 1960). The roots synthesize carbonic acid and carbonates from the soil, i.e. they also take part in the assimilation of carbon dioxide; previously this function was attributed solely to the leaves. Grapevine roots contain pigments which contribute, in the first place, to the supply of nitrogen to the plant (reduce nitrates to an available condition) and, secondly, to the reduction of carbon, which reaches the roots in the form of carbonic acid and carbonates (Chkuaseli, 1966).

The isotope of phosphorus, P^{32}, absorbed by the roots participates in the synthesis of nucleoproteids and lipoids, while nitrogen absorbed in the form of the NO_3 radical is reduced to NH_3 (ammonia) and used to form amines, amides and many other organic compounds (Kolosov and Ukhina, 1954).

The root system influences the photosynthesizing organ, the leaves (B. Rubin and Germanova, 1959) by regulating the oxidation-reduction regime in them. Any weakening of this interrelationship sharply reduces the tension of the oxidation processes in the leaves and causes disturbance of their physiological functions (Ivanov, 1953).

There is no direct relationship between the amount of water transpired by a plant and the amount of salts absorbed by the root system from the soil solution. The roots and the colloidal particles of the soil exchange ions, the sources for the exchange in the plants being H^+ and HCO_3^- ions, whose occurrence in the bleeding sap shows that they are bound by the components of the cell protoplasm (Sabinin, 1955, and others).

The root system plays an essential role in the production of chlorophyll. Delayed root formation inhibits shoot growth and chlorophyll production in the first leaves, but with the

emergence of the rootlets shoots start to grow and chlorophyll appears in the leaves. Absorptive and synthetic root activity depends upon the environmental temperature. Low temperatures cause a sharp decrease in the activity of the root system, in the absorption of minerals and their conversion to organic compounds (Kolosov, 1962). The albino sunflower grafted on a green sunflower plant turns green, probably due to a substance produced by the root system of the green plant and transported to the above-ground parts (Lyashchenko and Lyashchenko, 1957). Thus, the synthesis of specific substances by the roots is responsible for normal chlorophyll formation in the leaves.

With adequate supply of oxygen to the root system all the non-organic nitrogen that enters it from the external environment combines with the organic nitrogen; the initial assimilation of soil nitrogen in the form of asparagine, glutamine, allantine, and ulitruline occurs here. Kinetine, found in the roots, performs the specific functions of a disintegration hormone during nucleic acid hydrolysis, i.e. prevents yellowing of the leaves and increases the resistance of the plant to injury (Mothes, 1956). Mothes believes the roots to be the main site of amide and amino acid production and calls them "a sort of a chemical kitchen". Previously it was assumed that synthesis of complex organic compounds occurred only in the leaves (Rubin and Germanova, 1959).

The fact that organic compounds are synthesized in the roots gives grounds to believe that a cycle of organic substances takes place in plants. Some of the assimilators flowing from the leaves evidently pass as sucrose to the roots, where they undergo thorough processing and interact with the elements of mineral nutrition. Then the mixture of the substances formed, at least some of it, apparently returns to the above-ground organs for further transformations.

Simple organic substances (glucose, fructose, sodium acetate, and glycol) are intensively supplied to the plant from the soil solutions by way of the root system, the process occurring much more rapidly in the light than in the dark (Kuzin *et al.*, 1956).

Roots grown in culture media containing nutrient salts and sugars (sucrose) are capable of synthesizing proteins, nucleoproteins, and hormones, which are needed for the

formation of meristem. These roots branch off, grow mostly in length and only slightly in thickness. Only their primary meristem is active, the secondary meristem remaining passive. The meristematic cells, like cells of the plant embryonal tissues, are rich in nucleic acids and their nucleoproteid content approaches the high nucleoproteid level in the cells of microorganisms (Sabinin, 1955).

The meristematic parts of the root system react to all changes occurring not only in the surrounding soil, but also in the air, and exert a direct influence on the above-ground part.

Producing an active effect on the solid phase of the soil, the root system aids in passing of some of the absorbed ions into solution and in assimilation of carbonic acid from the soil and the supply of the products of its transformation to the above-ground assimilating organs (leaves), where they take part in carbohydrate photosynthesis. The activity of the leaves is ensured by means of water and products formed in the root system, which is, in turn, continuously supplied with energy and building materials in the form of carbohydrates assimilated by the leaves. The role of different roots in plant nutrition is different; rootlets covered with numerous hairs (known as fibrous roots) are the most active.

The root system excretes into the soil organic substances, namely sugars, organic acids, mineral compounds of phosphorus, potassium, and other substances facilitating the dissolution of minerals and development of microorganisms, which, in their turn, contribute to the production of adequate conditions for plant nutrition in the area of active root function.

According to Timiryazev, the root system "moves" towards food and water, though the plant stays put. The mobile nutrients naturally penetrate the roots, while the relatively immobile compounds can be "approached" by the absorbing roots. To provide the plant with nutrients and moisture the roots must spread over a vast area and have numerous absorbing rootlets and root hairs.

Lomonosov (1711-1765), Kostychev (1886) and other Russian scientists pointed out that the content of humus depends on the root system. The roots provide the main background for the distribution of humus in the soil, while the water-soluble organic substances washed out of the

above-ground parts of the plant are merely superimposed on this background, their main bulk being evidently fixed in the top soil horizon.

Nutrients and water move in the plant rather rapidly. The products of assimilation travel along the roots at a rate of 0.7 to 1.5 m/hr, minerals rise at a rate of 2 to 4 m/hr, and water, up to 14 m/hr (Kursanov *et al.*, 1960).

New regularities of plant nutrition with active participation of the roots and root rhizosphere were revealed, which allows many aspects of root system activity to be studied on a new basis and the problem of increasing the yield of fruit plants to be solved in a new way.

Thus, the roots of plants, including the roots of fruit plants, fulfil the following main functions:

(1) absorption of water and mineral substances dissolved in it from the soil, and the production of amides, amino acids, proteins, lipoids, nucleoproteids, hormones, and other organic substances;

(2) excretion into the soil of various substances, such as sugars, organic acids, and mineral compounds of phosphorus, potassium, etc., which contribute to the dissolution of mineral substances and the development of rhizospheric microorganisms;

(3) exertion of active influence on the solid phase of the soil and on passing of part of the adsorbed ions into solution, also assimilation of carbonic acid from the soil and supplying the above-ground organs with the products of its conversion. The root system provides the leaves with the necessary water and nutrients which it produces itself, and is in turn supplied with energy in the form of carbohydrates produced by the leaves. The root system regulates the oxidation-reduction processes in the leaves (Ivanov, 1953);

(4) interaction with mycorrhiza and with the rhizospheric system of organisms;

(5) accumulation and storage of nutrients;

(6) penetration of root newgrowths into new, yet unused layers of soil containing water and water-dissolved nutrients;

(7) propagation of fruit plants (sour cherry, plum, raspberry and some others) by shoots sprouting from roots;

(8) anchoring the plant in the soil.

The roots of fruit plants are as active as the leaves, and the root system as a whole, interacting with the above-ground system, plays an important role in the growth, development, and fruiting of the plant. It follows from this that the fruit grower must have a good knowledge of the structure and activity of the plant as a whole and be able to carry out daily control of the harmonious work of both "laboratories"—the leaves and the roots.

Types of Root Systems of Trees and Shrubs

In the process of evolution the different varieties of trees and shrubs acquired many types of root systems differing considerably in structure and in their distribution in the soil and partly above ground. A classification of the underground organs is essential for successful studies of the above-ground and root systems of plants. In our opinion, of considerable interest in this respect is the classification of the root system of trees and shrubs suggested by Krasilnikov (1968), who believes that with a greater number of characteristics than he used an improved classification of the plant root system could be worked out. His data are presented in Figs. 2, 3, and 4.

It is well known that many trees and shrubs are cultivated from cuttings or shoots, or by grafting on stocks, which leads to changes in plant architectonics and in the distribution of the root system in the soil. For this reason we suggest the following classification of root systems into four types:

(1) root systems of *generative origin*, grown from seeds (usually forest and frequently nut varieties);

(2) root systems of *generative origin*, obtained by grafting on stocks grown from seeds (sometimes forest and decorative varieties, and usually fruit varieties);

(3) root systems of *vegetative origin*, i.e. grown from runners (strawberry), layers (Paradise apple, quince, gooseberry, etc.), or stem cuttings (olive, currant, etc.);

(4) root systems also of *vegetative origin*, but grown from shoots sprouting from the roots of parent plants and forming new roots on them. This type is characteristic of some tree and shrub varieties, especially of sour cherry, plum, and all varieties of raspberry.

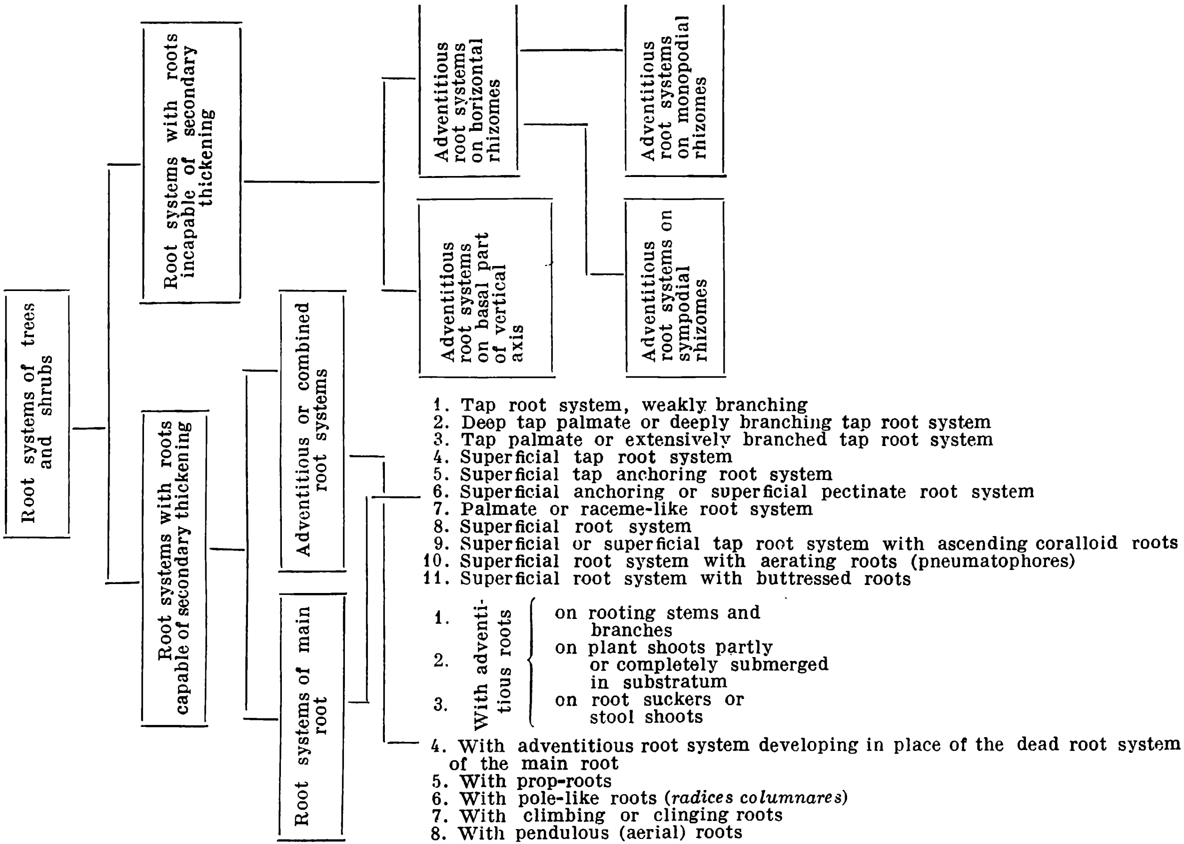


Fig. 2. Subdivision of the root systems of trees and shrubs (after Krasilnikov)

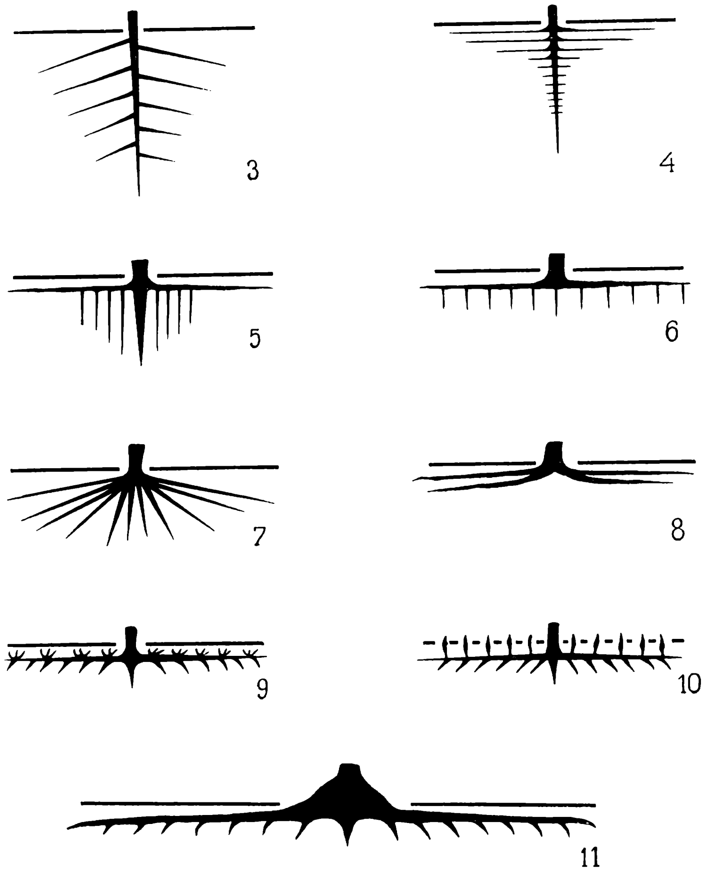


Fig. 3. Types of primary root systems of trees and shrubs:
1—tap weakly branching root system; 2—deep tap palmate or deeply branching tap root system; *3*—tap palmate or greatly branching tap root system; *4*—superficial tap root system; *5*—superficial tap anchoring root system; *6*—superficial anchoring or superficial pectinate root system; *7*—palmate or raceme-like root system; *8*—superficial root system; *9*—superficial or superficial tap root system with ascending coralloid roots; *10*—superficial root system with aerating roots (pneumatophores); *11*—superficial root system with buttressed roots.

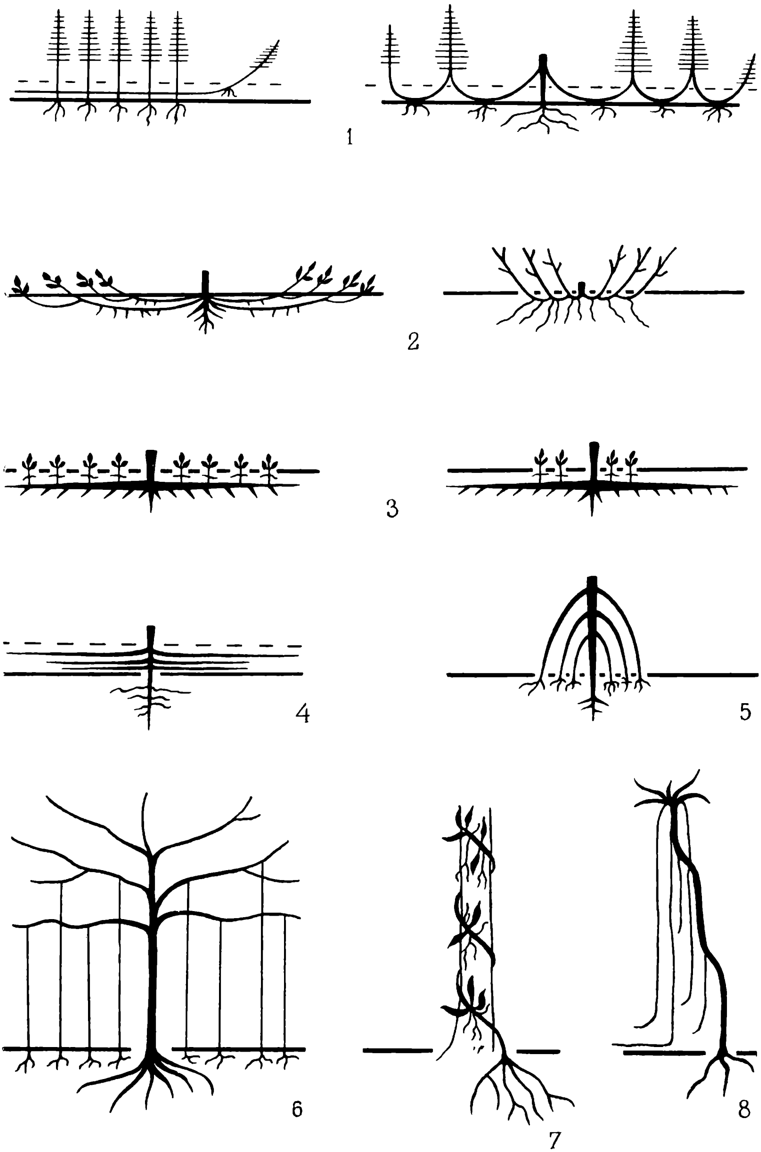


Fig. 4. Types of secondary and combined root systems of trees and shrubs:

1—with the adventitious roots on the rooting stems and branches; *2*—with the adventitious roots on the plant shoots partly or completely submerged in the soil; *3*—with the adventitious roots on the root suckers or stool shoots; *4*—with the adventitious system developing in place of the dying-off main root system; *5*—with prop roots; *6*—with polelike roots (radices columnares); *7*—with climbing or clinging roots; *8*—with pendulous (aerial) roots

Types of Roots

Distinction is made between *main* and *adventitious* roots in accordance with their origin. The main root is of primary structure and is encountered only in a seedling (root stock), where it develops from the radicle of the seed embryo (Fig. 5). Adventitious roots develop from auxiliary buds of plants.

In relation to their *distribution in the soil* the roots are grouped as follows:

(1) *horizontal* roots lying more or less parallel to the soil surface at a depth of 30 to 100 cm and more;

(2) *vertical* roots, or "sinkers" growing vertically downwards along earthworm holes and sometimes along soil cracks, reaching as deep as 2 to 10 m and more.

The horizontal roots spread over the surface soil horizons, where microbiological processes are most active and valuable nutrients accumulate abundantly.

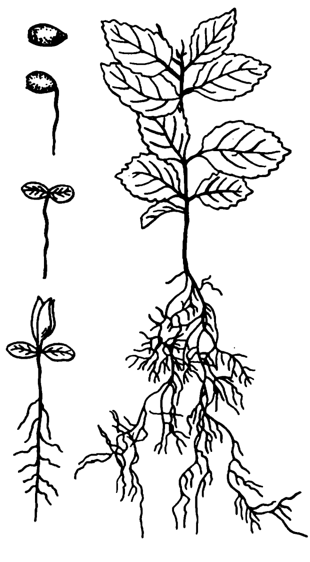


Fig. 5. Sprouting of seed embryo and the root system of a pricked off seedling

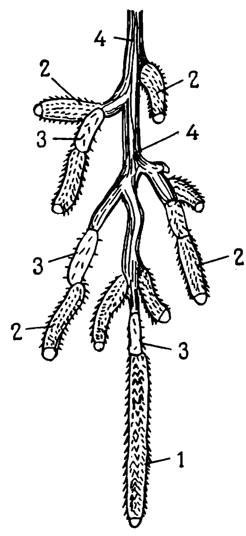


Fig. 6. Fibrous roots of an apple tree:

1—growing, or axial roots; *2*—absorbing, or active roots; *3*—intermediate roots; *4*—conducting roots (×3.5)

The vertical roots convey water and nutrients and apparently obtain certain trace elements from the deeper soil horizons, and anchor the tree in the soil. Growth of active roots proceeds longer in the deeper horizons than in the horizons closer to the surface.

The roots are further divided into the following two groups according to their length and thickness:

(1) *skeletal* (scaffold) and *semiskeletal* roots, which are long (from several centimetres to several metres) and thick (up to several centimetres), and include roots of the zero order (the primary roots), and roots of the first, second, and sometimes third orders of branching.

(2) *fibrous* roots, which are short (between fractions of a millimetre and several millimetres, sometimes several centimetres long) and thin (1 to 3 mm in diameter). These are roots of the third (sometimes), but more often of the fourth to seventh, orders of branching. They are also called fibres (or nets). All absorbing roots belong to this group.

The factor serving as the basis of our classification of fibrous roots is their physiological function, determined phylogenetically by their anatomy and morphology.

We studied the roots of pine, spruce, fir, apple, pear, sour cherry and other species and we believe that they have four types of fibrous roots. We will give a detailed description of these four types (Fig. 6) in an apple tree: (1) growing, or axial; (2) absorbing, or active; (3) intermediate, and (4) conducting (V. A. Kolesnikov, 1955, 1959, 1962a, b, 1966a).

1. The *growing*, or *axial* roots are of primary structure and white in colour; the meristematic zone is thicker than the central wood cylinder. Their main functions are to grow considerably in length, thus ensuring rapid spread of the root system to new (fresh) soil layers, and to produce lateral branchings—nets (fibres) of absorbing roots. The growing roots are usually much fewer in number than the absorbing roots, but are thicker and longer (the growing roots have a length of 10 to 25 cm, while the absorbing roots grow to 3 or 5 mm). Like in all plants, a great number of growing roots arise in fruit tree seedlings after replanting, particularly in spring. These roots have no mycorrhiza and develop secondary growth.

2. The *absorbing* or *active* roots are sometimes called *feeding* roots. They are also of primary structure, white in

colour and translucent. Their main function is to absorb water and mineral substances from the soil and to transform them into organic compounds. The absorbing roots are distinguished by high physiological activity. At the peak of active root growth they form the most numerous group of roots accounting for over 90 per cent of the total number of roots on a plant; for example, they number tens of thousands in apple tree seedlings and millions in mature trees. They usually range from 0.1 to 4 mm in length and from 0.3 to 3 mm in thickness. The absorbing roots have mycorrhiza (in the form of symbiosis) and often do not develop secondary growth; they have a short life (15 to 25 days or sometimes a few months—autumn growth) and then rot away ("self-thinning").

3. The *intermediate* roots are of primary structure, light-grey in colour, sometimes with a violet tinge. They are mostly former absorbing roots about to atrophy; the rest are growing roots about to turn into secondary structure and become conducting roots. The presence of intermediate roots is a sure sign of root growth: it shows that the root system has been active for at least one to three weeks.

4. The *conducting* roots are of secondary structure, light- to dark-brown in colour. They usually arise from roots which grew previously and whose atrophied primary cortex (Fig. 7) has been replaced by a thinner secondary cortex; they grow thicker year after year until they become semi-skeletal or skeletal roots. Their main function is to conduct water and nutrients in both directions.

The growing and absorbing roots consist of a root-cap, a growth zone, and an absorption zone covered with root hairs invisible to the naked eye. These are followed by a zone of dying root hairs and suberized cells (intermediate zone), and then by the conducting zone proper (Fig. 8). A conducting root is initially yellowish grey, but after the primary cortex dies and is sloughed off and a secondary cortex (periderm) forms, it turns light-brown.

The conducting roots that grow downwards differ somewhat in structure. The large vessels of the secondary xylem in apple and oak roots lying at a depth of 2.2 m are three to five times as thick as in roots lying in the top layer. At a depth of more than 1.5 m the root loses its typical structure and its xylem becomes considerably deformed.

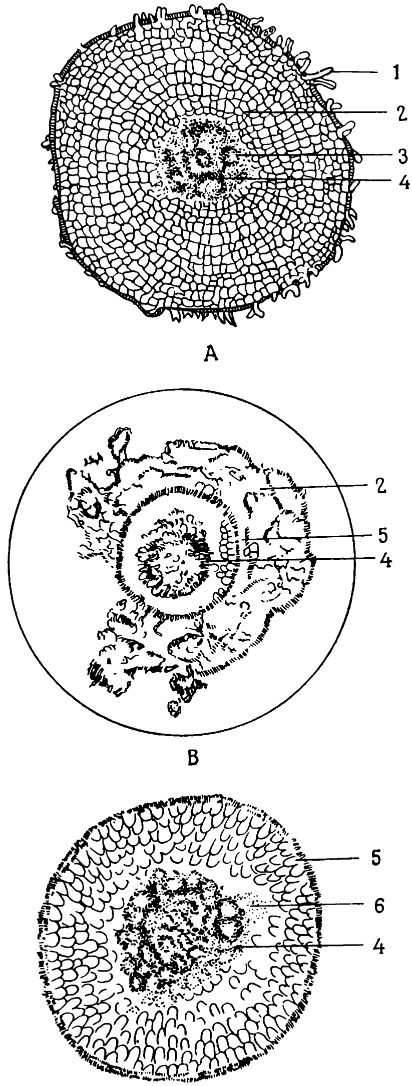


Fig. 7. Secondary growth of roots:
A—apple root of primary structure; *B*—dying-off of primary cortex; *C*—root of secondary structure: *1*—root hairs; *2*—primary cortex; *3*—pericycle; *4*—central cylinder; *5*—periderm; *6*—vessels of secondary xylem (greatly magnified) (after Muromtsev)

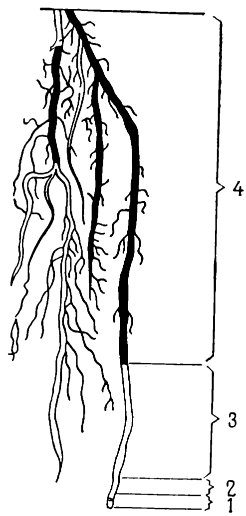


Fig. 8. The root of an apple tree: *1*—root cap; *2*—cell division and cell elongation zone; *3*—absorption zone; *4*—conducting zone

On deep-lying roots the root endings are well developed, the absorbing roots are better developed on the whole, whereas the growing roots are less developed (Onishchenko, 1955).

Root Hairs

A *root hair* is a tubular outgrowth of the outer wall of certain cells in the epidermis of the absorbing zone of the root. It is a cell and has a protoplasm with a nucleus. The cell wall is very thin (12 microns), which facilitates water intake.

Root hairs are found in most tree and soft fruits. They increase the absorbing surface of the root systems by a factor of 2 to 10 (Fig. 9). For instance, a one-year-old Anis apple seedling develops by the end of October over 17 million root hairs with a total length of about 3 km (Muromtsev, 1948, 1962; V. A. Kolesnikov, 1958).

The root system of herbaceous plants grows to a considerable length. For example, the total root length in a one-year-old rye plant reaches 600 km, and the total number of root hairs, 15 thousand millions (their length is 10,000

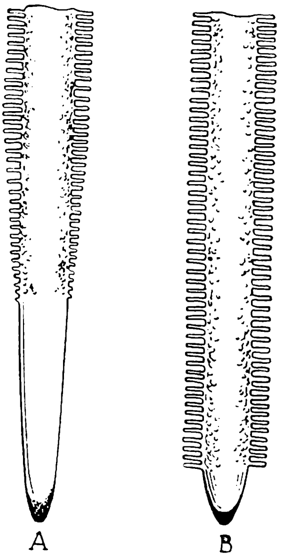


Fig. 9. Root hairs on actively growing (*A*) and on nongrowing (*B*) root (after Muromtsev)

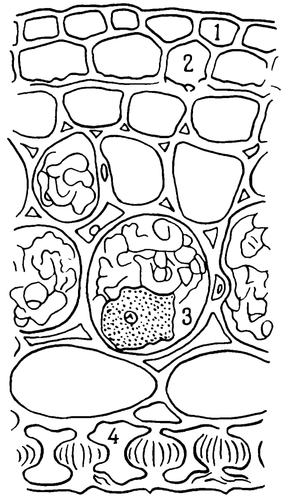


Fig. 10. Mycorrhiza of wild sweet cherry:
1—epidermis; *2*—primary cortex; *3*—root cells containing fungal hyphae in a state of decomposition; a nucleus is seen; *4*—Ф-shaped cells with endoderma cells lying immediately below (after Dominik and Jagodzinski)

km). The length of roots of a rye plant increases daily by 5 km, and that of its root hairs, by 80 km. It is this extensive contact of the root hairs with the soil that ensures adequate absorption of water and nutrients by the plant (Dadykin, 1952).

The absorbing roots and root hairs of the various fruit plants differ in shape, length, and thickness (Fig. 11). The length of root hairs of apple trees raised in a humid chamber in laboratory conditions was: 328 microns for the Chinese apple, 216 microns for the wild apple, 196 for the Siberian crab apple, 101 for the Doucin III, 92 for the Doucin V, 63 for the Paradise VIII and 61 microns for the Paradise IX (Muromtsev, 1962).

Muromtsev divided the primary root of an apple seedling from base to tip into 3 mm-long portions and found that the number of root hairs was, respectively, 400, 500, 475, 325, 300, 300, and 300 per sq mm of surface. The tip of the root (the last 3-mm portion) had no root hairs.

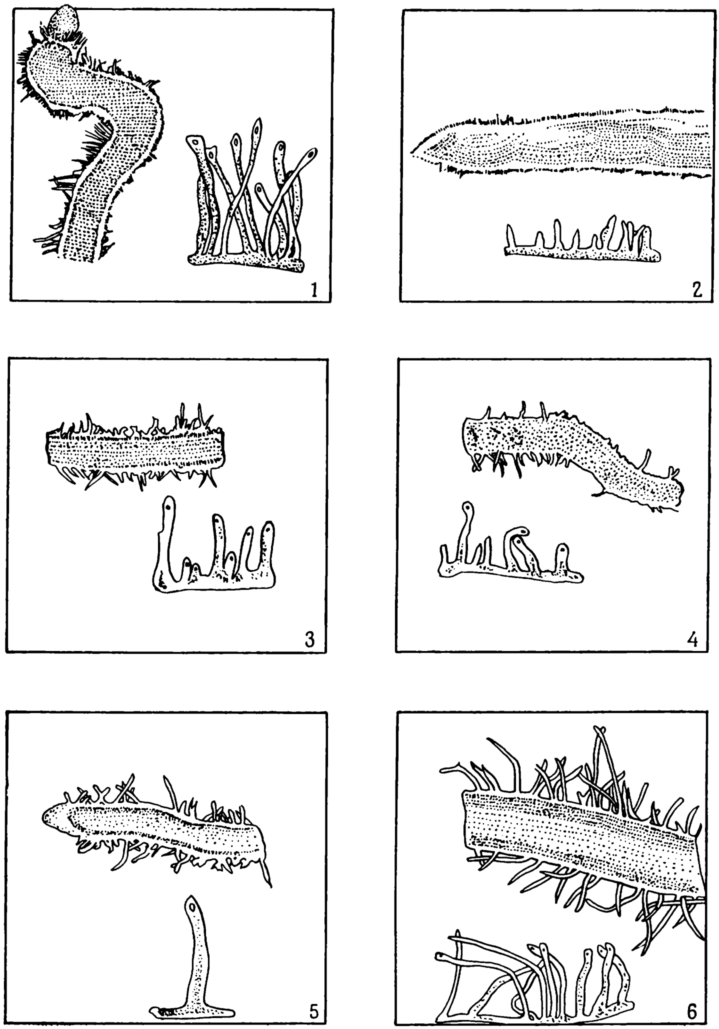


Fig. 11. Absorbing roots (thicker ones) and root hairs (thinner ones), greatly magnified:
1—wild apple; *2*—wild pear; *3*—hazel; *4*—plum; *5*—raspberry; *6*—currant

The Mycorrhiza (or Root Fungus) and Rhizosphere of Plants

The mycorrhiza on the root system of fruit plants is of great importance. The first detailed studies were made by Kamensky (1883), who found that the sweet pinesap (*Monotropa hipophitis*) had threads of an unknown fungus instead of root hairs.

Many researchers believe that mycorrhiza is useful for higher plants. It apparently occurs on all pome fruits, stone fruits, nuts, subtropical fruits, and berried fruits (Fig. 10). According to data at our disposal, the apple, pear and other species have mycorrhiza (Fig. 12). (Dominik, Jagodzinski, 1964; V. A. Kolesnikov, 1958).

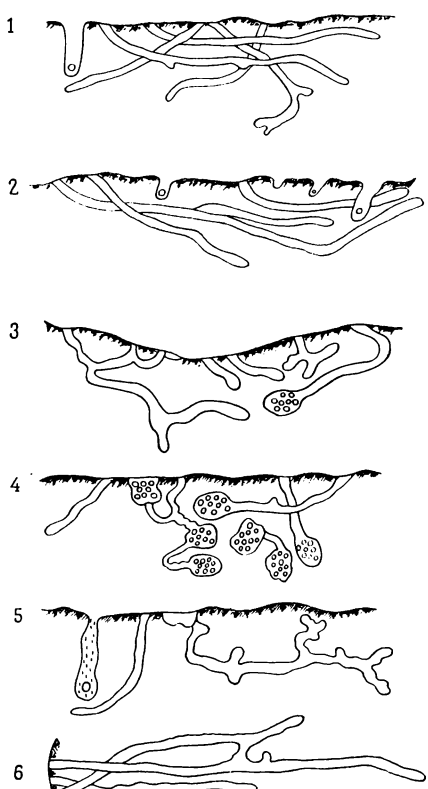


Fig. 12. Mycorrhiza of fruit and berry species: *1*—wild apple; *2*—wild pear; *3*—hazel; *4*—plum; *5*—raspberry; *6*—currant

Mycorrhiza develops only on absorbing roots when moisture is at an optimum level. A decrease in soil moisture leads to the death of mycorrhizas; if moisture then increases sufficiently, new absorbing roots appear with new mycorrhiza on them.

Roots form a symbiosis both with mycorrhiza (soil fungi), which lives either inside the root cells of some plants or on the root surface of others, and with rhizospheric organisms. Rhizosphere, which is the term for the myriad of microorganisms enveloping the roots, plays an important role in the plant-soil interrelation. The root excreta enrich the surrounding soil in numerous compounds and promote the activities of bacteria and fungi. Beyond the rhizosphere the amount of bacteria and fungi sharply reduces.

The soil is abundantly populated with microorganisms: 1 hectare of soil contains tens and hundreds of thousands of millions of them. The mass of live microorganisms in the surface layer of the Central-Asian sierozem (gray desert soil) amounts to about 7 tons per hectare of soil. As a result of the development of new microorganisms and dying off of old ones (which occurs 2-3 times a month or 8-12 times during the vegetative season in the middle belt) during the summer months tens of tons of organic compounds rich in nucleoproteids (bodies of microorganisms) decompose in the surface layer of each hectare of the soil (Krasilnikov, 1958). In spring, when the soil gradually warms up, the amount of microorganisms increases, while in summer it reduces by many times to increase again with autumn colds.

The microorganisms produce substances which stimulate plant growth. Many researchers hold that the roots are the main source of formation of organic substances in the soil. It is due to root activities that adequate amounts of humus substance, microorganisms and worms accumulate in the soil.

Microorganisms specific for the particular plant are selected in the root zone; these are different from the bacteria prevailing in the soil. The main factor which determines the specific nature of the rhizosphere bacteria is the root excreta, since the life of the rhizosphere bacteria is connected with metabolic products in the plant. That is why we studied changes in the population of rhizosphere bacteria according to the phases in the development of gooseberry (V. A. Kolesnikov, Tepper and Voronchikhina, 1965). The

microorganisms were recorded by using two successive washings (see Table 1).

Table 1

Content of Microflora for Different Conditions of Gooseberry Root System

Time of Sampling (phase of development of above-ground part)	Washing No.	Content of microflora, %			Condition of root system (percentages of roots)	
		soil (sporogenous) and actinomycetes	specific (rhizospheric)	miscellaneous	dead	live
Breaking of buds	I	84.0	1.0	15.0	65	35
	II	90.0	0	10.0	76	24
Flowering and shoot growth	I	—	—	—	—	—
	II	40.1	40.8	19.1	50	50
Fruit setting	I	0.2	78.2	21.6	55	45
	II	14.0	75.4	10.6	57	43
Ripening of berries	I	74.0	12.8	13.2	79	21
	II	58.4	10.0	31.6	85	15
Leaf fall	I	76.7	12.7	10.6	82	18
	II	67.9	18.0	14.1	88	12
After leaf fall	I	3.1	87.5	9.4	42	58
	II	24.8	58.8	16.5	54	46

The first sample taken on the 3rd of May during the breaking of buds at a soil temperature of 8°C contained many dead roots. The rhizosphere was made up predominantly of soil microorganisms, the bulk of which were actinomycetes and fungi.

The second sample was taken on the 2nd of June at a soil temperature of 8.5°C at the beginning of active growth of absorbing roots. The live-to-dead-root percentage ratio became 50:50, the microflora content changed: the rhizospheric microorganisms amounted already to 40.8%, and the soil microorganisms to 40.1%. The rhizospheric microorganisms (non-sporogenous) formed small-celled semitransparent colonies.

The next sample was taken on the 22nd of June at the start of fruit setting. The root system was active: live roots constituted 43%, dead ones 57%. The percentages of

specific rhizospheric non-sporogenous bacteria for the two consecutive samples were 78.2 and 75, respectively. The fourth sample (August 18) was taken when the berries were already ripe. The activities of the roots had greatly reduced, there were many dead roots. The microflora changed accordingly in favour of the soil sporogenous bacteria, the percentages for the soil microorganisms and specific bacteria being 74 vs 12.8, and 58.4 vs 10.8, respectively.

The next sample was taken after the berries were gathered (September 12). The dying-off of roots was still pronounced. The amount of sporogenous microorganisms continued to grow too. The last sample was taken after the leaf fall (November 3). The respective percentages for the autumn growth of the roots were 58 and 46. The amount of non-sporogenous rhizospheric bacteria increased (87.5 and 58.8 per cent). Hence, the composition of the rhizosphere microflora was determined by the condition of the root system, i.e. by the prevalence of growth over dying-off or vice versa.

Two forms of prevailing bacteria developing on gooseberry roots were singled out as pure cultures, and their species determined. These strains were conventionally designated as Nos. 3 and 4. On the basis of morphological, cultural, and physiological features No. 3 was classified as *Pseudomonas myxogenes* species, No. 4 as *Achromobacter nitrovorum*. Thus, a specific microflora develops on gooseberry roots. The greatest number of specific rhizospheric bacteria develop during the period of berry formation and after leaf fall when the growth of absorbing roots is intensive, whereas dying-off of roots is marked by prevalence of sporogenous bacteria and actinomycetes.

These facts prove the necessity and importance of further investigation of rhizosphere of all fruit plants.

Cyclic Renewal (Self-Thinning) of Roots

Du Hamel du Monceau was the first to observe in 1758 the dying-off, or "self-thinning", of roots, i.e. the replacement of rootlets by new ones, while Knight (1806) noted the absence of the tips of a main root in many trees. Studies on this important problem were started at the Pomology Department of the Timiryazev Agricultural Academy (Moscow) in 1920 both on fruit and forest trees (V. A. Kolesnikov, 1924 a, b, 1930, 1967).

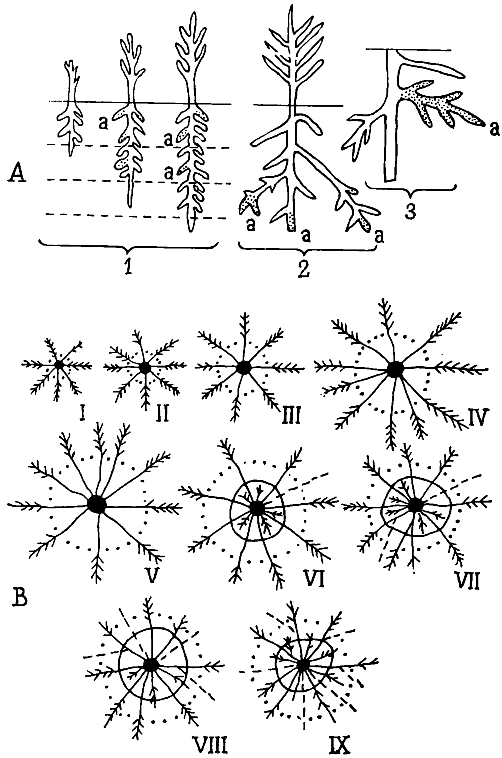


Fig. 13. Dying-off of apple tree roots:
A—types of the dying-off process: *1*—separate roots (*a*); *2*—root ends (*a*); *3*—fibrous roots (*a*) (after V. A. Kolesnikov). *B*—dying-off of roots during nine age periods: *1*—dying-off of thin roots inside the dotted line contour); *2*—formation of new roots (inside the continuous line contour) (after Krestnikov); *3*—dying-off of skeletal roots (broken lines), the fourth type of the dying-off process (after Kuznetsov). Roman figures indicate the age periods

Three types of dying-off of fibrous roots in apple and pear seedlings were established (Fig. 13).

1. Systematic dying-off of short lateral active roots, first on the main root, even in the first or second weeks of growth, and then, with further growth, on longer roots of the next orders of branching (Fig. 13, *1* and *2*).

2. Dying-off of the tips of the main root and those of roots of higher orders. For example, in 50 to 85 per cent of the seedlings the tips of the main root died off over a length of 5 to 20 cm from the base (Table 2), and a lateral root appeared and continued the growth of the main root.

Table 2

Percentages of Seedlings with Dead Tips on Main Root

Species	Number of seedlings	Percentages of seedlings with a dead tip on the main root
Apple	90	85
Pear	24	50
Sour cherry	2	50
Pine	8	40
Ash	3	33

The growth of seedling root systems during the vegetative season is marked by the following regularities (Table 3): (a) the longer the roots, the greater the number of roots with dead tips among them; (b) the number of roots with dead tips decreases directly with the appearance of new orders of branching because the roots of new orders are always shorter than the roots of the preceding orders; (c) root systems of the pear acquire new tips and lateral roots more often than those of the apple.

3. Dying-off of fibrous roots and sometimes their replacement by a single root or a group of new roots (Fig. 13, *3*).

Table 3

Total Number of Seedling Roots and Percentages of Roots with Dead Tips in Relation to Root Length for All Orders of Branching

Item	Total	Length of roots, mm: 0.1-5	5-10	11-15	26-30	36-40	66-70	101-105
				Apple				
Total number of roots	12,142	7,821	2,774	810	124	63	13	7
Percentage of roots with dead tips	2.0	0.3	2.6	5.2	9.7	16.7	20.5	43.0
				Pear				
Total number of roots	7,776	3,635	1,746	979	162	87	17	7
Percentage of roots with dead tips	4.5	1.4	3.9	7.4	11.1	14.3	23.5	33.9

Between July 23, 1921 and June 7, 1922 the root system of pear seedlings grown at the nursery of the Timiryazev Academy developed as follows (Table 4).

Table 4

Development of Root System of Pear Seedlings at the Timiryazev Academy Nursery

Item	1921			1922	
	July 23	August 30	September 30	May 17	June 7
Number of seedlings	3	4	5	3	2
Height of seedlings, cm	10.5	14.4	17.0	17.0	17.0
Depth of root system, cm	37.5	49.5	60.0	60.0	73.0
Number of roots	3,068	7,306	8,328	7,669	8,717
Total length, m	30.7	73.1	83.3	76.7	87.2

As a result of dying-off, by the spring of 1922 the number of roots on each seedling had reduced by 659 totalling 6.6 m in length. The process was especially pronounced during October, a month usually favourable for the life activities of root systems in the Moscow Region. Assuming 200,000 seedlings per hectare the length of the roots that had died off during the autumn alone amounted to 1,320 km with a total weight of 75 kg. But if one takes into account that the dying-off of seedling roots continues from May throughout the whole summer, the amount of dead roots will be much greater. It will be still greater for orchards where trees with powerfully developed root systems grow.

Our findings were confirmed by Orlov (1955), who showed that the annual rate of dying-off of the absorbing roots for 25-year-old spruce amounted to 2 tons per hectare.

The dying-off and renewal of the roots of fruit plant seedlings, or a cyclic renewal of roots, is a natural process in the life of all trees and, most likely, herbaceous plants as well. We call such thinning of roots "root shedding", since it rather resembles leaf shedding in evergreen plants. This term, in our opinion, conveys concisely and clearly the essence of this phenomenon, which is extremely important for any plant.

The studies on the dynamics of the dying-off of roots were renewed by the Pomology Department of the Timirya-

zev Academy in 1952 (Voronchikhina, 1956), with gooseberry as experimental material. It is a suitable plant in this respect, for its dead roots, as distinct from apple roots, do not decompose and do not disappear for a long time. We observed the effect of weather conditions and environment on the intensity of root shedding. A pronounced increase in the dying-off of roots grown in autumn is observed at bud bursting. During the shoot growth and blooming root shedding greatly reduces, whereas in the period of ripening of the berries it reaches the maximum rate because at this time all the nutrients are utilized for cropping. After the leaf fall a new wave of root growth starts resulting in decreased root shedding.

With deterioration of the environmental conditions root shedding increases. Thus in 1952, which was a year of favourable weather, the average annual root shedding was 25 per cent, in 1953—45 per cent, and in 1954—72 per cent. Irrigation carried out in 1954 somewhat decreased root shedding. On the tenth day after watering there were 25 per cent living and 75 per cent dead roots on the plants; the figures for the plants which remained unirrigated were 15 and 85 per cent, respectively.

In 1964 and 1965 root shedding in raspberry was studied (Voronchikhina, 1966). The effect of the environmental conditions on the process is shown in Table 5.

Table 5

Percentages of Live and Dead Absorbing Roots for Raspberry Kaliningradskaya in Relation to Seasonal Conditions

Month	Ten-day period	1964		1965	
		live, %	dead, %	live, %	dead, %
May	III	71	29	79	21
June	I	77	23	61	39
	II	77	23	62	38
	III	39	61	89	11
July	I	61	39	94	6
	II	67	33	87	13
	III	65	35	76	24
August	I	68	32	92	8
Average for season	—	65.3	34.7	80.0	20.0

In 1964, which was very dry and hot, root shedding in raspberry in summer time reached 34.7 per cent. In 1965 it was only 20 per cent due to adequate rainfall. In June 1965, when there was a sudden drop in temperature, root shedding ranged between 38 and 39 per cent.

In the middle belt of the USSR root shedding takes place from April to November and in the south of the country, where winters are not so severe, it apparently proceeds throughout the year. Maximum root shedding occurs before the beginning of the growing season and during the early part of it and during intensive growth and fruit ripening.

The root shedding recorded by us and other researchers is measured in kilogrammes and even tons per hectare of fruit and forest species. In the course of dying-off and renewal the root system constantly invades fresh, unused layers of soil and subsoil. It spreads out from the stem in circular belts, dying off in one place and growing in another (in the direction of the branch spread periphery), providing normal conditions of growth and cropping.

A correct conception of the growth and dying-off of plant roots is of great theoretical and practical importance. As is well known, after harvesting and ploughing the root system rots and produces humus, thus improving the soil structure. Many researchers, however, neglect the fact that the dying-off of the roots of all trees, and evidently those of herbaceous plants as well, occurs continuously over the entire growing season. The organic mass of dead root tissue reaching several tons per hectare also contributes to the accumulation of humus and the improvement of the soil structure.

The process of dying-off and renewal of roots is irregular and depends on the environmental conditions, which are often very different for the above-ground part and the root system, and this may lead to different growth and dying-off in both systems, and may disturb the correlation between the root and above-ground systems, i.e. adversely affect the life activities and cropping of fruit plants.

The phenomenon of self-thinning was confirmed by Rogers (1939), Muromtsev (1953), and other researchers.

To establish the relationship between the development of the root system and the above-ground part of a tree Kuznetsov (1967), lecturer of the Department of Pomology of the Timiryazev Academy, in cooperation with agronomist

Stepanov, studied at the Snezhetok state farm (the Tambov Region) changes in the root system of a wild apple tree (Antonovka Obyknovennaya) according to five age periods of the life cycle after Schitt (1958). The sample trees were selected by Schitt's method of biological inspection, while the root system was studied by Oskamp's method or with the use of cuts, digging trenches 1 m deep at distances of 2, 3, 4, and 5 m from the tree trunk. The nature of distribution of live and dead skeletal and semiskeletal roots according to soil layers (Table 6), and the depth of rooting in soil and subsoil (Table 7) were established.

Table 6

Percentages of Live and Dead Roots of an Apple Tree During the Last Five Age Periods According to Soil Horizons

Soil Horizons, cm	Age Period									
	5th		6th		7th		8th		9th	
	total	live	total	live	total	live	total	live	total	live
0-20	20	100	14	50	7	50	0	0	3	0
20-40	27	100	39	78	35	81	54	40	35	20
40-60	25	100	26	95	24	84	33	30	32	44
60-80	22	100	21	100	8	100	13	73	24	79
80-100	6	100	0	0	0	0	0	0	6	86
Total roots	100	100	100	83	100	76	100	41	100	47

Table 7

Percentages of Radial Distribution of Live and Dead Roots of an Apple Tree According to Age Periods

Distance of Trench from Trunk, m	Age Period									
	5th		6th		7th		8th		9th	
	total	live	total	live	total	live	total	live	total	live
2	34	100	29	86	39	89	39	78	42	69
3	25	100	26	84	38	81	23	47	24	44
4	23	100	24	83	13	75	24	0	19	36
5	18	100	21	72	10	64	14	0	15	0
Total roots	100	100	100	83	100	76	100	41	100	47

The tabulated data give a vivid picture of the process of dying-off of skeletal roots of an apple tree: (1) during the 5th age period all skeletal roots are active, whereas beginning with the 6th and through the 9th age period root shedding takes place. During the last age period the relative number of live roots somewhat increases due to the appearance of new roots which evidently grow from the root collar of the tree; (2) shedding of skeletal roots prevails in the surface layer of the soil (0-10 cm) and in the deepest layer (80-100 cm). We attribute this to the unfavourable conditions in the upper horizon due to droughts, and to the lack of air in the deepest layer.

The dying-off of the whole root system starts in the manner described, followed by natural root shedding in the other soil horizons and terminating with the death of the apple tree. Owing to the shedding of skeletal roots, the bulk of the root system of a fruit tree begins to decrease from the fifth age period.

According to our classification, the dying-off of skeletal and semiskeletal roots should be considered the fourth type of root shedding in woody species.

Studies of the biological regularities of root shedding were continued at our Department from 1962 onwards by Kuznetsov and Krestnikov (1967) on an apple tree through all the nine age periods (after Schitt). They confirmed that in all age periods the stand thickness of skeletal and fibrous roots in the soil horizons decreases from the stem to the branch spread periphery and often far beyond it. The total length of the skeletal roots increases especially beginning with the first and through the seventh period because new roots sprout systematically from the base of the root system (and evidently from the root collar too).

The highest stand thickness of fibrous roots, which are most active before the third age period, is observed at the boundary of the branch spread periphery and beyond it. The pattern changes sharply beginning with the fourth age period, when owing to the appearance of new roots the area of greatest thickness shifts from the periphery to the base of the tree trunk. Thus, beginning with the fourth age period (after Schitt) two processes—centrifugal (away from the trunk) and centripetal (towards the trunk)—take place.

During all subsequent age periods the bulk of fibrous roots is confined to the area of the branch spread, while the

zones of greatest stand thickness move within its boundaries, depending on the process of shedding and new growth of roots and their activity, which is in turn associated with branch activity. The maximal total length of fibrous roots, in particular that of absorbing ones, occurs in the fourth age period, i.e. when the branch spread and root system of the whole tree (first to fourth periods) are still growing, owing to which the highest yield of fruit is obtained.

Beginning with the 5th age period, i.e. with the second half in the life cycle of a tree, when its development follows a downward curve, the total length of fibrous roots declines. The poorer the environmental conditions and orchard care, the quicker is this process. Improved orchard care not only reduces root shedding but also causes growth of new roots.

The extent of fibrous root branching in an apple tree is much greater between the first and fourth age periods than in the fifth to eighth periods.

All the above-stated experimental data on the cyclic renewal of roots and branches enabled us to represent this process graphically (see Fig. 13).

Effect of External Factors on Root Growth

The root growth of fruit trees and shrubs is greatly influenced by external conditions: moisture, aeration, soil temperature, content of nutrient substances. This is particularly true for the growth of absorbing roots.

With lack of water in the soil the roots always extend in the direction of damper places. At a moisture content close to the wilting coefficient the growing roots transfer to the secondary structure at an earlier stage. Root growth may be arrested before the soil moisture content reduces to the wilting coefficient. Therefore when the soil moisture content decreases to a value exceeding the wilting coefficient by 2-3 per cent for sandy and 3-4 per cent for clayey soils, orchards should be irrigated. The growth of active roots in apple slows down even with a short-term reduction of soil moisture. Therefore, orchards and berry plantations should be irrigated annually, especially during droughty seasons.

An excess of water (due to abundant precipitation, irrigation, or high ground-water level) hinders soil aeration,

and thus greatly injures the growth of the root system; fruit trees often stop growing, yield no fruit, and even die. For example, the roots of grapes do not extend into ground waters where there is a shortage of air. High ground waters are especially injurious to fruit trees from the moment they enter the cropping period.

The roots of fruit plants are highly sensitive to the lack of oxygen, particularly during intensive growth of active roots, which commonly occurs in spring and autumn. The intensity of respiration of roots in apple trees reduces perceptibly when the soil oxygen concentration drops below 8-9 per cent and when the carbon dioxide concentration exceeds 5-6 per cent (Childers and White, 1949). Excessive humidification of the soil strongly inhibits the growth of absorbing roots, changes their colour from light-brown to black, and causes their death. Even a thirty-minutes' exposure of an absorbing root to a medium devoid of oxygen suppresses the growth of root hairs on its growing portion. Root hairs do not develop in water plants either. Inadequate aeration suppresses the development of root hairs more strongly than it does the growth of absorbing roots.

Root growth also depends on the temperature. Tanaka reported from Japan in 1932 that root growth occurs in strict accordance with their heat requirements: the roots of plums and peaches start growing in early February at a soil temperature of 4 to 5°C, the roots of pears and apples, in mid-February at 7 to 8°C, the roots of figs and grapes, in late March at 9 to 10°C, the roots of chestnut and persimmon, in mid-April at 12°C, and the roots of citrus fruits, in mid-May at 16 to 18°C.

The roots of fruit trees in the southern Ukraine began growth at a soil temperature of 5 to 6°C, irrespective of the depth of penetration. In pots, the roots of apples began to grow at 4 to 5°C, those of pears at 6-7°C, the roots of sour cherries at 6°C, and the roots of apricots and peaches at 12-22°C (Gushchin, 1941).

In winter, at temperatures ranging from 1.7° to 7.2°C apple root growth was weak, but reached its peak at temperatures between 7.2 and 20.5°C. In winter, only the deepest-lying roots grew (Nightingale, 1935; Rogers, 1939).

Tolsky (1905) revealed that the horizontal roots of pine grew at a temperature of 6°C, while the vertical roots started growing at 0.1°C. Root growth in cloudberries occurred

at temperatures ranging between 0 and 3°C (Dadykin, 1952). In the summer apple tree roots grew at deeper levels. Studies in root observation cabins showed that vertical root growth in Slavyanka apple was 0.2, 0.3, 0.7 and 1.1 mm per day at temperatures of 0.4, 0.9, 3.8 and 6.0°C, respectively (Kolesnikov, 1954).

Absorbing roots of apple begin to absorb nitrogen at a soil temperature of 0.6°C, this process becoming intensive at a temperature of 7.2°C (Batjer, Magness and Regaimbal, 1939). Oxygen deficiency in the roots markedly affected the supply of mineral substances to apple seedlings (Villiers, 1939). The growth of absorbing roots is more often arrested by low temperatures than that of axial roots. Thus, axial roots can grow at lower temperatures.

High soil temperatures inhibit root growth. For instance, in the Crimea and in California roots lying in the top layers of the soil cease to grow in hot summer months. The reason for the summer slump in the growth of fruit plant roots in the southern regions of the USSR is undoubtedly the high temperature of the soil (higher than 25-30°C), along with the lack of soil moisture and excessive yield of the tree. In Armenia, at high summer temperatures the growth of apricot roots slows down even in irrigated orchards (Mikoelyan, 1956).

Root growth is greatly influenced by the content of the basic nutrition elements.

Nitrogen stimulates primarily the growth of absorbing roots and then the growth of axial roots. The lack of nitrogen reduces the growth of absorbing roots, while excessive nitrogen suppresses the growth of both groups of roots. Nitrogen may increase the weight of roots by 50 per cent, owing to which their absorbing surface will increase by 200 per cent. After the introduction of nitrogen the number of fibrous roots per 1 cm section of a skeletal root of Pippin Litovsky apples was three times as great as in the versions with phosphorus and potassium and in the controls. Under such conditions the absorbing roots grew relatively more intensively than the axial ones (Rubin, 1958).

Introduction of nitrogen enhances the growth of the above-ground part of the plant. As reported from the Mleyevo Fruit-Growing Research Station, the weight of the aerial portion of apple seedlings grown in soil cultures (a vegetat-

ive experiment) showed a greater increase in all variants with nitrogen than the weight of the root system. Thus, in the nitrogen and phosphorus (NP) variant the weight of the aerial portion was 133 per cent and that of the root system 7 per cent greater than in the control plants. In the nitrogen, phosphorus and potassium (NPK) variant this increase was 50 and 13 per cent, respectively, i.e. the weight of the aerial portion had increased less as compared with the root system. The apple root system produced more fibrous roots in the variants with nitrogen.

Phosphorus promotes the branching of the root system, i.e. the sprouting of lateral roots. A shortage of phosphorus leads to slow and stunted growth of the aerial portion. At the beginning of their development plants must be provided with adequate phosphate nutrition.

Potassium facilitates the branching of roots, too, and increases the weight of the roots more efficiently as compared with that of the above-ground portion. With a shortage of potassium root branching is suppressed.

Calcium forms compounds with pectin substances and improves the strength of the roots. Its presence in the growth zone of all roots is essential. With calcium deficiency growth ceases and lateral roots rapidly die off.

The growth of the root system of fruit plants is greatly enhanced by soil treatment, particularly by fertilization and irrigation.

Types of Root Growth. Two types of root growth are distinguished: (1) in length, and (2) in girth.

The growth of the growing and absorbing roots in length increases the absorbing surface of the root system, while the growth of the conducting roots in thickness improves the supply of the plant with water and nutrients and provides a better stability.

After sowing, the radicle of a dicotyledon seed first gives rise to the main, or primary, root, then the hypocotyl develops, the cotyledons swell, and the stem budlet starts to grow. The main root (of zero order) continues its growth to a length of 10 to 20 cm and then produces branches. During a growing season the Chinese apple tree develops up to seven orders of branching, most of the roots being of the third and fourth orders (V. A. Kolesnikov, 1924; 1930). Our observations were confirmed by investigations

carried out in Bulgaria by Stoichkov in 1934. Most of the other fruit species have 5 to 6 orders of branching.

Up to 40,000 roots with a total length of 230 m developed from a year-old Chinese apple seedling during a growing season in the Moscow Region. One-year-old seedlings of wild and Siberian apples, and of pear and sour cherry in particular, develop a considerably smaller amount of roots (both in respect to the length and number) within the same period of time.

Most seedling roots are very short. Thus, 65 per cent of the roots of an apple tree vary in length from fractions of a millimetre to 5 mm, while 19 per cent are 5.1 to 10 mm long. The respective figures for a pear tree are up to 43 and 23 per cent. The longer the roots, the smaller their amount. The average root length (coefficient of roots) in one-year-old seedlings of fruit and forest species is comparatively constant: for Siberian apple it is 6 mm, for Chinese apple 7 mm, wild pear and cherry 9 mm, sour cherry 8 mm, mahaleb cherry 14 mm, pine 3.5 mm, spruce and fir 7.5, ash 10, and Chinese scholar's tree 16 mm. The overwhelming majority of roots of cropping fruit trees are also short. The average length of the fibrous roots of Anis seedlings, as a rootstock, is also constant, equalling 3.5 mm. This constancy was confirmed by experiments made in Germany on forest species by Schreiberg and Gesselink in 1926.

Grown-up fruit trees have millions of roots with a total length of dozens of kilometres.

Over the period of 1952-1966 we studied in the Moscow Region the growth of the above-ground part and the root system of 11- to 22-year-old Antonovka Obyknovennaya apple trees grafted on Anis seedlings and found that during each growing season apple shoots grew 1.5 to 2.5 months, the most active growth (6-17 mm per day) lasting only 15 to 25 days, usually between late June and early July. Shoot growth slowed down towards the beginning of July, even if the trees were watered at that time, which may be attributed to the established rhythm of plant vital activity under certain natural conditions.

The period of shoot growth in cropping pears, plums and sour cherries is also relatively short. The longer were the shoots on an apple tree, the larger were the leaves on

it. This should be taken into account when growing not only apple, but all fruit species.

In the middle belt of fruit growing an apple tree begins to form fruit buds, lignify its shoots and prepare the above-ground system for winter at the end of June. Taking into consideration the established rhythm of the vital activities of a plant, it is possible—by appropriate treatment (intensified nutrition and irrigation in May to the middle of June for the Moscow Region and even earlier for regions closer to the South)—to stimulate long shoots with larger leaves and thus intensify photosynthesis and formation of fruit buds.

During the same years the root system of the same apple trees differed somewhat in growth from the above-ground part; observations were carried on for twelve years, including five years with two waves of growth per growing season, five years with three waves, one year with one wave, and one year with four waves. Such a disparity between the dynamics of growth of active roots in apple during a growing season may be attributed to different environmental conditions (Fig. 14). It was also found that the dynamics of root growth in different varieties of apple grafted on one and the same rootstock (Anis seedlings) was different even for one and the same area of an orchard. A similar picture was observed in studies of active root growth in sour cherry and plum.

Thus, during a growing season active roots of fruit plants grow in one to three waves, more seldom in one wave, and still more seldom evenly. Growth waves are caused by many factors, both internal (species, sort, rootstock, rhythm of vital activities of the plant) and external (moisture, nutrients, soil treatment techniques, and so on).

In an apple tree root growth lasted from 5 to 7 months, and up to 9 months if snow covered unfrozen soil. During six of 12 years of observations, the absorbing roots grew more intensively in autumn (before frosts set in) than in spring.

The periods of root growth may differ with the depth. In apple, for instance, in spring, when the upper roots start growing, the lower ones are still at rest, whereas in summer the deeper roots are more active, as a rule.

In sour cherry the root activities were reduced in upper soil layers with excessive moisture, while in the deeper

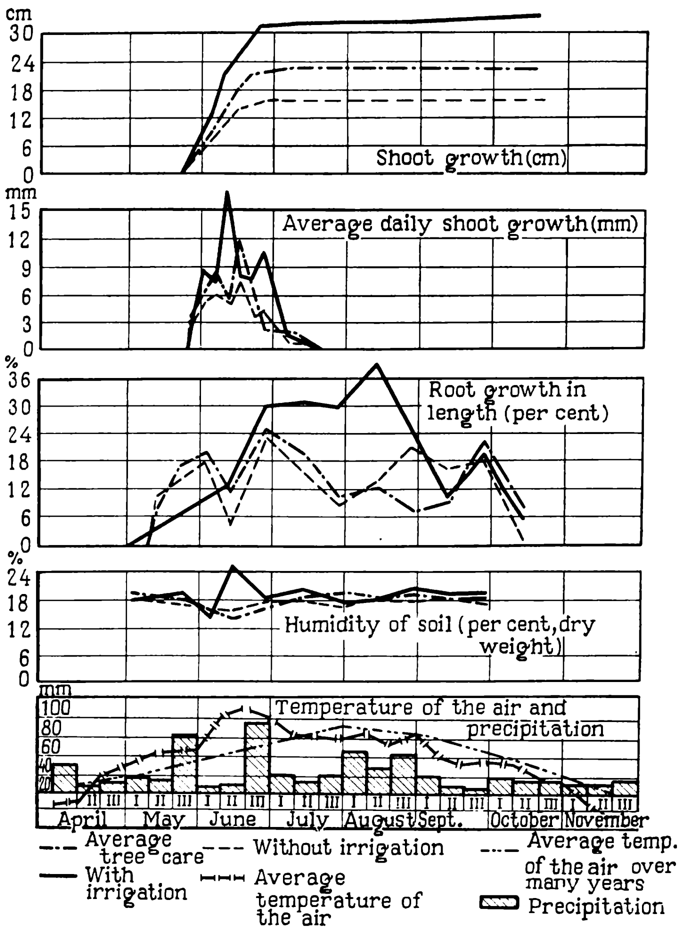


Fig. 14. Dynamics of shoot and root growth in Antonovka Obyknovennaya apple on Anis seedling. Shoot growth continued for about 2 months, with only one month (June) of vigorous growth (6-17 mm per day). Without irrigation root growth occurred in three or four waves, while with irrigation it occurred in two waves but was considerably more vigorous

horizons with a lower moisture content root growth was quite intensive (Fomenko, 1963). This fact should be taken into consideration in determining the time and depth of fertilizing.

Studies using the "glass panel" method showed that roots grew more intensively during the night than in the daytime (in apple and plum).

In spring, the growth evidently begins earlier than leaf expansion, but under certain conditions, in particular when there is excessive soil moisture, the reverse may take place. The most important thing, however, is that the root mass must be formed by the time the leaf blades start to unfold.

The growth and development of a plant (growth of absorbing roots, bursting of fruit and vegetative buds, flowering, and appearance of the first leaves) in early spring are due to the nutrients stored in the roots, trunk, and branches during the previous year. By the time the leaves start to form, however, the stored nutrients are already exhausted, and so new absorbing roots have to start functioning in order to supply the leaves with moisture and nutrients. If this does not occur (with a surplus of soil moisture in spring), the newly developed leaves and flowers will shed, as was the case several times with apple trees in the Crimea, Kuban, the Moscow Region and some other areas of the USSR. That is why the fruit grower should adapt soil treatment to spring conditions and the state of the soil in order to ensure adequate root growth, especially by the time of mass appearance and start of leaf blades and flowering.

With the aid of appropriate soil treatment techniques it is possible to grow the required amount of absorbing roots in good time and to prolong their growth during the vegetation period even during the late autumn and winter months. For example, in the middle belt of the USSR it is possible to maintain root growth for 9 months instead of 5 to 7, and in southern areas with mild winters—throughout the whole year. This is all the more important because absorbing roots that appeared in autumn and winter are rich in moisture and organic substances. The greater their amount formed by the tree in autumn, the faster and more abundantly they will develop new roots in spring. Consequently, the longer the period of root growth and the

greater the amount of roots, particularly in autumn, the easier it is for the tree to produce a high yield the following year. In our opinion, the crop highly depends on the growth of absorbing roots in the autumn of the previous year.

Formation of the Root System

The characteristics of a root system differ with the root origin (from seeds or stem), plant variety, rootstock, natural conditions, and management. Fruit trees are commonly obtained by grafting on seedling rootstocks, the root systems of which develop from seeds and because of this are younger than the rest of the plant organism. Such root systems are more viable and possess higher resistance to unfavourable environmental conditions. They usually penetrate deeper into the soil than the root systems formed from stems, i.e., from older plant organisms which developed long ago from seeds and have already yielded several croppings.

The rates of horizontal and vertical root growth differ and, consequently, root distribution in soil horizons is also different. In the Moscow Region, for instance, the roots of fruit trees extended horizontally on the average 20-36 cm from the trunk and penetrated to a depth of 17-33 cm; in the Crimea the figures were 20-25 cm and 5-15 cm, respectively; in the Kuban area, 38 cm and 50-100 cm. This rather considerable difference should be taken into account when selecting and preparing the soil for an orchard and in subsequent management of the roots and soil. Sound management, for example deep ploughing, cultivation and fertilizing can increase the mass of roots below horizon A_0 in practically any soil, including soddy-podzolic.

The growth and localization of the thin, fibrous, and absorbing roots may change, depending on the natural conditions and management: from early spring through late autumn, and even after defoliation the roots may grow on and off, die off, be cut off by cultivation tools, and then appear again in the same and in new soil layers.

As the root system of a seedling, and later that of a mature tree, spreads gradually, vast volumes of soil are invaded by thick and long main roots which carry hundreds of thousands of absorbing rootlets with tens of millions of root hairs.

Table 8

Characteristics of Papirovka and Antonovka Obyknovennaya Apple Trees Grafted on Different Rootstocks in the "Komsomolets" Orchard

Variety	Rootstock	Height of tree, m	Spread of branches, m	Spread of root system, m	Root system-to-branch spread ratio, m	Depth of rooting, m	Length of roots per 1 cu m of soil, m
Papirovka	Red-leaf paradise	2.50	2.65	6.30	2.42	2.60	251
	Paradise IX	2.40	2.45	6.60	2.69	3.40	263
	Doucin III	3.80	3.00	8.40	2.79	3.80	170
	No. 13-14	4.80	4.55	10.60	2.33	4.20	308
	Wild apple tree	4.10	4.20	10.20	2.43	4.40	275
Antonovka Obyknovennaya	Red-leaf paradise	2.55	1.75	6.00	3.40	3.20	177
	Paradise IX	2.80	2.55	6.20	2.43	3.60	222
	Doucin III	3.90	3.55	8.40	2.33	3.80	194
	No. 13-14	4.40	4.45	10.20	2.29	4.20	268
	Wild apple tree	4.00	4.15	9.90	2.39	4.20	256

The following two examples illustrate the effect of seed and vegetative rootstocks on the size and distribution of the root system of an apple tree, and also the growth and amount of fibrous roots in different soils and soil horizons.

The first example (see Table 8) shows that the size and distribution of the root system of 12-year-old apple trees in Michurinsk depended both on the rootstock and scion. It was also established (Budagovsky and Krysanov, 1966) that, irrespective of the scion, trees grafted on much-branched rootstocks No. 13-14, and wild apple trees possessed more powerful roots of superior length (per 1 cu m of soil).

The second example (see Table 9) illustrates that the growth and distribution of fibrous roots strongly depended on soil conditions; the soil was of one and the same type but differed slightly in each specific case (Negovelov and Solyanik, 1967).

Table 9

Number of Apple Tree Roots in Different Genetic Soil Horizons of Prikubanskaya and Predgornaya Fruit Growing Areas of Krasnodar Territory

Horizons	Number of roots per 1 cubic decimetre of soil profile at a distance of 3 m from the trunk for			
	leached chernozem	meadow-chernozem soil	compact chernozem	dark-grey forest soil
A_{plough}	2.53	0.30	0.20	0.08
A_1	5.85	1.93	5.43	4.35*
B_1	3.28	0.82	0.90	2.87
B_2		0.54	0.60	
BC	2.89	0.22	0.65	1.23
C	2.05	0.17	0.22	0.64

* Horizons $A_1 + A_2$

Horizontal roots of various fruit plants lie comparatively close to the surface. This is due to the fact that the upper genetic horizons are richer in nutrients, and also to the structure, density and moisture of the soil, and, finally, to the specific features of the species and the rootstocks on which the trees are grafted.

The spread of roots is limited by the mechanical resistance of the soil. Thus, roots spread freely at a soil dens-

ity of less than 30 kg/cm^2, with great difficulty at 30 to 60 kg/cm^2, and cannot penetrate the soil at a density of over 60 kg/cm^2. Ortsand layers of the soil are impenetrable for roots since their densities reach 300 kg/cm^2 (Gruzdev, 1956). Poor penetration of roots into the B_2-A horizons of soils along the Lower Don River (steppe sandy loam soil) was due, among other things, to the compact structure, high hardness (up to 60-80 kg/cm^2) and density (up to 1.70-1.80 g/cm^3) and low porosity (33-35%) of the soil (Vashchenko, 1966).

Rocks (subsoils) and soils mixed with pebbles are often impenetrable. Fruit trees planted on pebbles lying at a depth of less than one to two metres grow poorly and die off early.

In the case of dense, and in some places cemented layers or horizons covered with new layers of earth, the root system is arranged in layers. For instance, in the Kuban area (the Krasnodar District) the first layer of apple tree roots is found at a depth of 75 to 100 cm, the second—at a depth of 220 cm (Fig. 15); in the grey soddy-podzolic soil of the

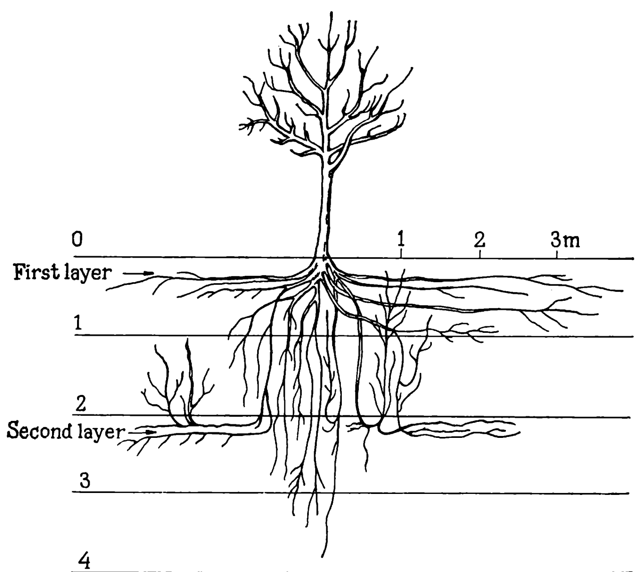


Fig. 15. Distribution of apple tree roots (the roots extend in two layers and then return to the upper layer)

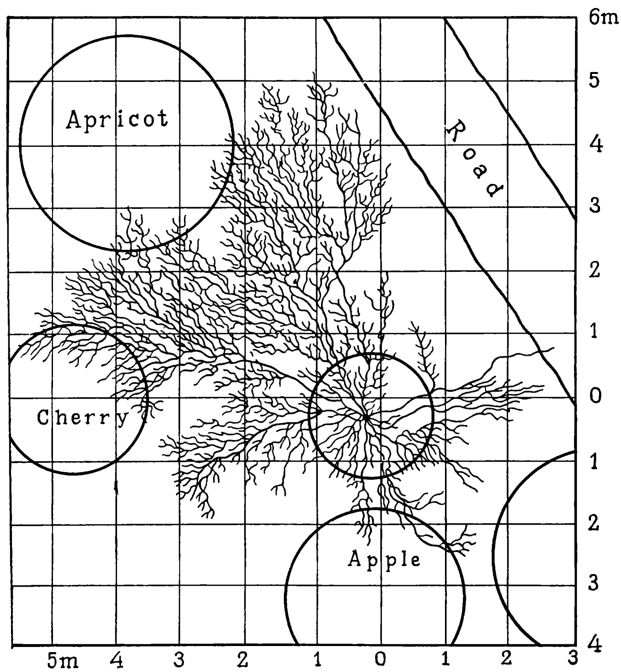


Fig. 16. Root system (horizontal section) of apple tree on wild apple rootstock; scion—12-year-old Candil Sinap. The roots spread freely to the area of the apricot and cherry roots, but avoid the area of a neighbouring apple tree or extend downwards, and do not spread under an adjoining road

middle part of the Volga area—at depths of 18 cm and 101 to 140 cm, respectively; and in the alluvial soil of the Don River plain in the Voronezh Region—at depths of 30 and 180 cm, respectively. Many roots return to the surface layers of soil from a depth of nearly 2 m.

The roots of fruit trees do not spread horizontally in tightly packed soil (for example, under a road; see Fig. 16).

Formation of the root system of fruit trees is greatly influenced by soil moisture. Thus, during excavation of apple tree roots in Crimean river valleys in an orchard with a high ground water table, about 60 m of roots larger than 1 cm in diameter were cut off from one 15-year-old tree when

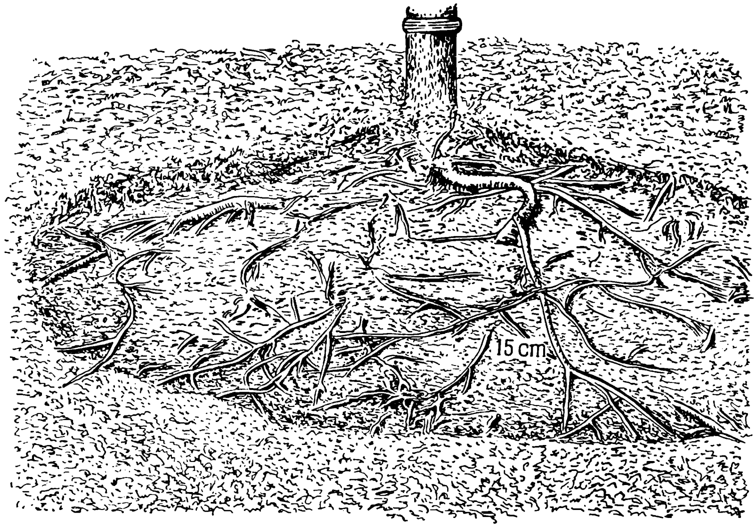


Fig. 17. Shallow distribution of apple roots (at a depth of 15 cm) in the Crimea on a plot with high ground waters

a 15-cm thick layer of soil was removed (Fig. 17), whereas in other orchards with more favourable conditions removal of a soil layer 20 cm thick exposed no roots more than 1 cm in diameter; they were found in deeper layers. Thinner roots can be found in considerable amounts in the surface layer at a depth of 3 to 10 cm, particularly in the northern fruit growing zone and in irrigated orchards.

With excessive soil moisture roots perish. First they change their light-brown colour to dark-brown, then they turn black and later acquire a darker tinge; the number of lenticels on them (the number of cracks on the cortex, to be more exact) increases, and the roots gradually perish (the cortex separates and rots) (Fig. 18).

With continuous hole irrigation a soil cylinder 1 to 1.5 m in diameter and 1 m deep and free of roots forms under the trunk; the roots die off or, more frequently, extend from the trunk close to the surface. Beyond the hole some roots turn strictly downward, others become very branched. In general, root systems always spread in the direction of optimal soil conditions, particularly as regards moisture.

Root depth in fruit trees depends **on** varieties and rootstock. In soddy-podzolic soils of the Moscow Region, for instance, the main mass of horizontal roots of apples penetrate to a depth of 75 cm and sometimes considerably deeper (Fig. 19), those of pears to 50 cm, sour cherry to 40 cm, and plum to 30 cm (Fig. 20), while the roots of a 16-year-old Antonovka apple tree on Chinese apple rootstock extend to a depth of 18 to 30 cm, on Doucin III to 20 to 35 cm, on Antonovka seedlings 25 to 40 cm, and on wild apple tree 24 to 25 cm (Ghena, 1957).

Radial root penetration of one and the same variety under similar natural conditions and management differs with the rootstock used. For instance, in Uzbekistan the roots of Rosmarine blanche apple on Chimgan apple rootstock spread 12.5 m and on local Chinese apple rootstock, only 6 m; the roots of a pear on vigorous rootstock spread

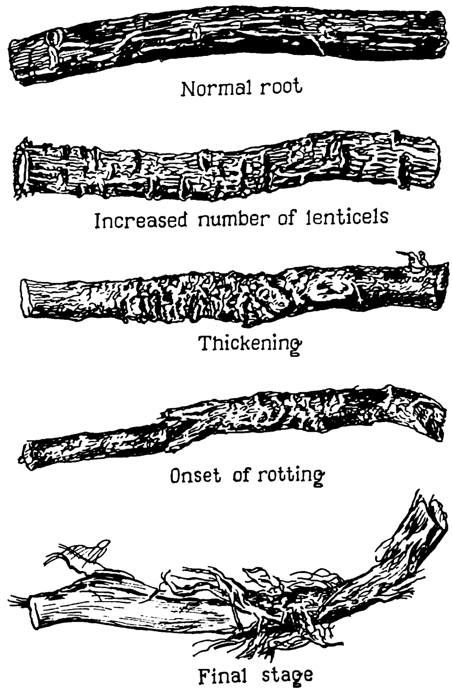


Fig. 18. Effect of excess soil moisture on apple roots

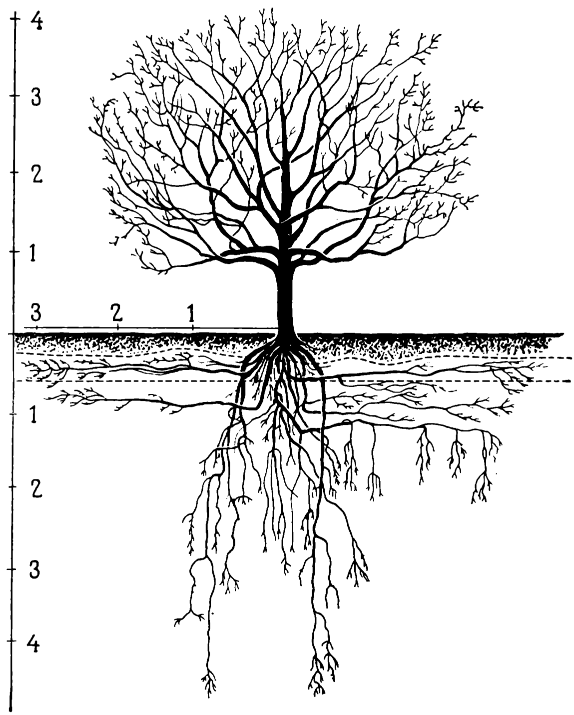


Fig. 19. A 20-year-old Antonovka Obyknovennaya apple tree on wild apple rootstock at Lenin State farm (Moscow Region); the roots penetrated to a depth of 4.5 m

8.7 m, and on quince only 3 m (Rybakov, 1956). In the Crimea the roots of an apple on wild apple rootstock spread over a distance of 2.5 m, on Antonovka seedling and Doucin III—3 m, and on Chinese apple and Anis seedling 3.7 m.

The distribution of the root system of fruit plants is greatly influenced by the specific characteristics of genetic soil horizons. Gruzdev (1937) found that in different zones of the European part of the USSR the main mass of roots was localized in the humus-accumulative horizon *A* and in the upper illuvial horizon B_1. For instance, the accumulative horizon *A* in the forest-steppe zone contained 78 per cent of the roots, in the chernozem zone 66 per cent, in

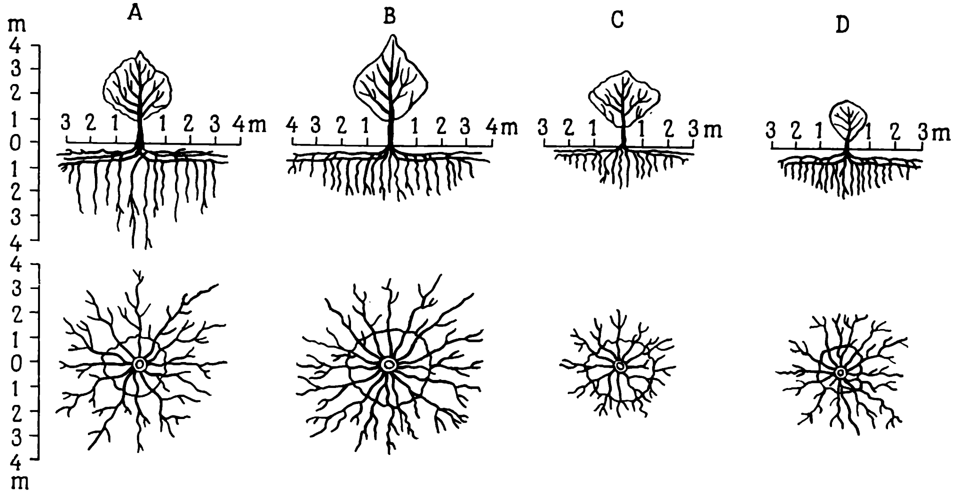


Fig. 20. Above-ground and root systems of 13-year-old fruit trees growing in the orchard of the Timiryazev Agricultural Academy:

A—apple; *B*—pear; *C*—plum; *D*—sour cherry. Circles drawn on the horizontal sections show branch spread

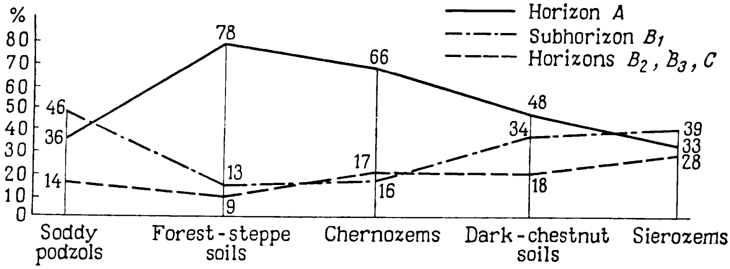


Fig. 21. Distribution of apple roots in genetic horizons for different soil zones of the USSR (after Gruzdev)

the dark-chestnut soil 48 per cent, in the soddy-podzolic soil 36 per cent, and in the sierozems only 33 per cent (Fig. 21).

In apple orchards growing in the middle part of the Volga area the bulk of the roots were evenly distributed to a depth of 90 cm on heavy loamy steppe-forest soil and to a depth of 40 cm on carbonate loamy chernozem (mainly in the humus horizon). In alluvial soils in Georgia 36 per cent of the root mass occurred down to a depth of 40 cm, while in Uzbek sierozems the main mass of apple roots grew 20 to 60 cm deep. On the meadow loamy soil in the Dniester flood-plain 66.9 per cent of apple roots were in the top 60-cm layer, while 60 per cent of plum roots, in the top 50-cm layer.

On the steppe (chernozem-like) sandy loam soils of the Lower Don valley, where compact illuvial horizons lie too close to the surface (higher than 60 cm), and on meadow soils with a high water table (1.25 cm and higher), fruit trees form a surface root system (Vashchenko, 1965).

The bulk (74.6%) of the horizontal roots of 18-year-old pear trees on heavy soils in the north of Karakalpakiya is found at a depth of 5 to 60 cm, and on light soils, at a depth of 40 to 100 cm (Dudkin, 1965).

There is a feature common to all fruit growing zones in the USSR and other countries. The diameter of the root spread in fruit trees is one and a half to two times and sometimes even three times the diameter of the branch spread, while the area occupied by the root system is five times

that of the crown. This approximate root spread-to-branch spread ratio persists from the second year after the tree is planted and throughout lifetime irrespective of the species, rootstock, and locality.

Horizontal roots of fruit species in the northern orchard zone extend to a depth of 30 to 50 cm, in the middle zone to 50 to 75 cm, and in the southern zone (Kuban) to 100 to 120 cm.

To study root growth, the root systems of 22 apple trees aged from 6 to 22 years were excavated by the skeleton method in the Moscow Region between 1952 and 1964. The above-ground part of the trees was also measured regularly. The diameter of the branch spread of a 7-year-old tree reached 2.4 m, that of a 15-year-old tree 3.8 m, and in a 22-year-old tree 6.9 m, which means that 5.6-, 3.8-, and 1.1-m strips of the inter-row space in an orchard were free of branches. With 7-year-old or younger trees about 75 per cent of the total space occupied by them was free of branches. With 15- and 22-year-old trees the figures were 50 and 15 to 20 per cent, respectively. Thus, when apple trees with a feeding area of 8 ×8 m achieved the age of 22 years, there was free access of light and air to the trees, and a space of 1 to 3 m between the rows, which allowed agricultural machines to operate normally (Fig. 22).

The root length of a 2-year-old apple seedling in the Moscow Region was 35 cm (after cutting). The diameter of the root system reached 3.5 m by the age of seven years, 5 m by the age of fifteen, and 8 to 9 m by the age of 20 to 22 years. Thus, with 8 ×8 m planting, the space free of roots was 4.5 m for 7-year-old trees and 3 m for 14-year-old trees, whereas in an orchard planted with 20- to 22-year-old trees the roots occupied the entire space between the rows and sometimes penetrated to the neighbouring inter-row space as far as 0.5 m.

After studying the interrelation between the growth of branches and roots we suggested that the spacing in planting apple trees be reduced (8 ×4 m instead of 8×8m). Plants of practically all varieties may be used for this, the best results being obtained with dwarf varieties of apple tree, while in the south—trees grafted on dwarf rootstocks may serve the purpose. In the Crimea apple trees grafted on Paradise apple or Doucin have been planted so for over 100 years. Apple trees grafted on Paradise apple trees grow

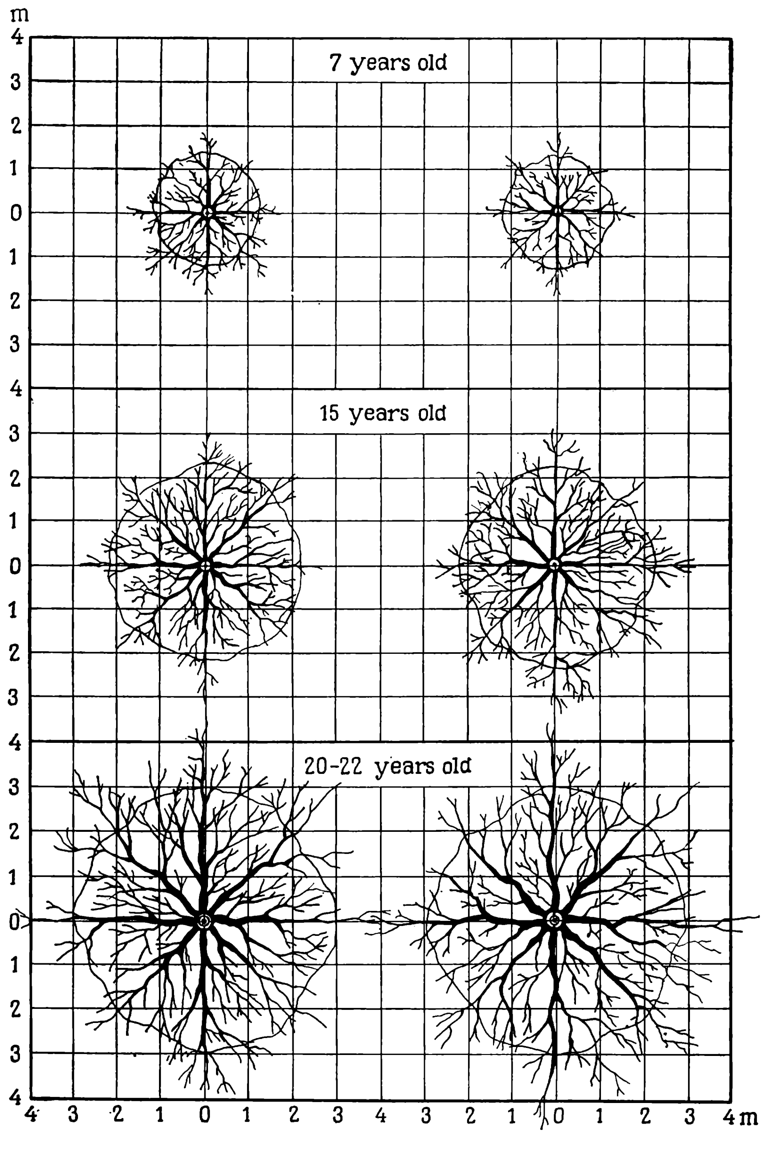


Fig. 22. Branch-to-root spread relation at different age periods (at the age of 7, 15, and 22 years) in Antonovka Obyknovennaya apple on Anis Seryi seedling (horizontal section)

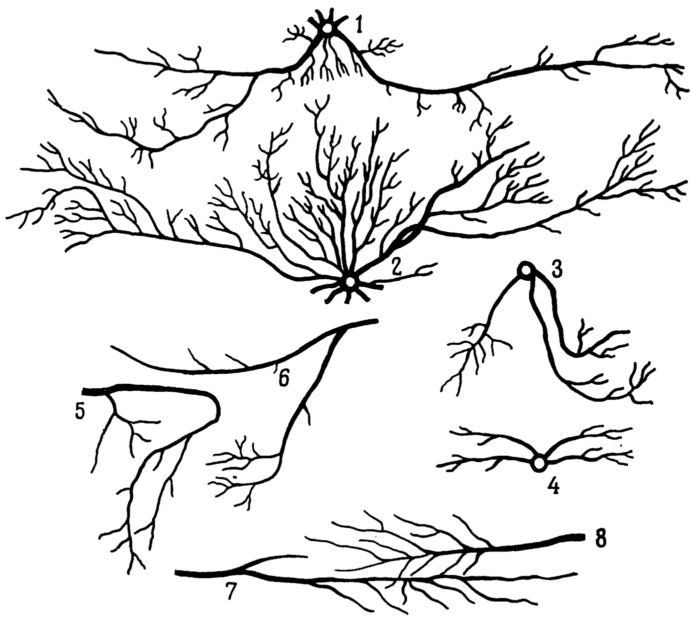


Fig. 23. Behaviour of the root systems of same and different fruit species growing in close proximity:

1 and *2*—peach trees (own-rooted); *3* and *4*—apple trees; *5* and *6*—apple trees; *7*—apple trees; *8*—sweet cherry tree

in an orchard for 20 to 25 years and those grafted on Doucin for 30 to 40 years; then they are uprooted, while the rest of the apple trees on vigorous rootstocks yield fruit for 50-70 years and even longer.

The root systems of some fruit trees (peach, for instance) avoid a zone occupied by the roots of a neighbouring tree of the same species or variety and usually go deeper, but they freely intertwine with the roots of a different species or variety (Fig. 23). On the other hand, the root systems of many other fruit trees of the same species may not only intertwine but even intergrow. Further research is needed to explain these phenomena.

Vertical roots are also distributed at different depth, depending on many factors. For instance, the root system of sour cherries grown from green grafts in the Moscow Region was not as powerful (judging from separate skeletal

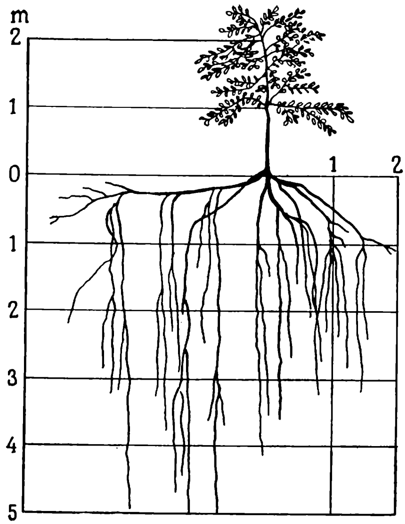


Fig. 24. Eight-year-old Vladimirskaya sour cherry on Mahaleb cherry rootstock (Krasnodar Territory). The roots penetrated 5 m deep; soil—the third terrace of deep chernozem

roots) as that of the grafted trees, but was more ramified. The roots of own-rooted plum trees grown in Moldavia and the Moscow Region are found in the soil layers closer to the surface as compared with the grafted trees.

Under appropriate conditions the roots penetrate deep into the soil rather quickly. Thus, in the Kuban Region the roots of vigorous grafted fruit trees aged 4 to 12 years were found at a depth of 3 to 5.5 m (Fig. 24), and even 9.5 m, whereas in the Crimea the roots of 30-year-old trees did not extend deeper than 1 to 1.5 m. In the Crimea the roots of dwarfing rootstocks (Paradise apple and quince) extend to a depth of 4 to 5.5 m.

The depth of root penetration depends on soil conditions, species (scion), and rootstock.

Excavations of Reinette de Champagne and Candille Sinap apple trees (at the Chkalov state farm in the Crimea) revealed almost no vertical roots, which could be attributed to the high ground water table and unfavourable physical properties of the soil; both these factors inhibit the downward growth of roots.

At the same state farm, on another site with high ground waters the roots of a 25-year-old Reinette de Champagne apple tree grew to a depth of only 1.3 m; the total root length

was 533.6 m, the vertical roots accounting for only 77 m and the horizontal ones for 456.6 m, of which 216.6 m were within the branch spread and 240 m beyond it. The number of vertical roots on seven excavated apple trees accounted for 13.6 to 64.7 per cent of the total number of roots, and the root length, for 11.2 to 58.12 per cent of the total length of the roots. In the Michurin orchard at the USSR Exhibition of National Economy Achievements (Moscow), where the ground water table is high, the vertical roots of a 25-year-old Doch Blankovoi pear tree on wild apple rootstock were few in number and did not grow deep.

On different soils of Moldavia the roots of apple, plum, apricot, and quince penetrated down to 2 m and those of pear, to 2.5 m. In Uzbekistan, the roots of Rosmarine Blanche apple on Siberian apple rootstock grew to a depth of 6.2 m, while those of a tree on Arabian Baba rootstock

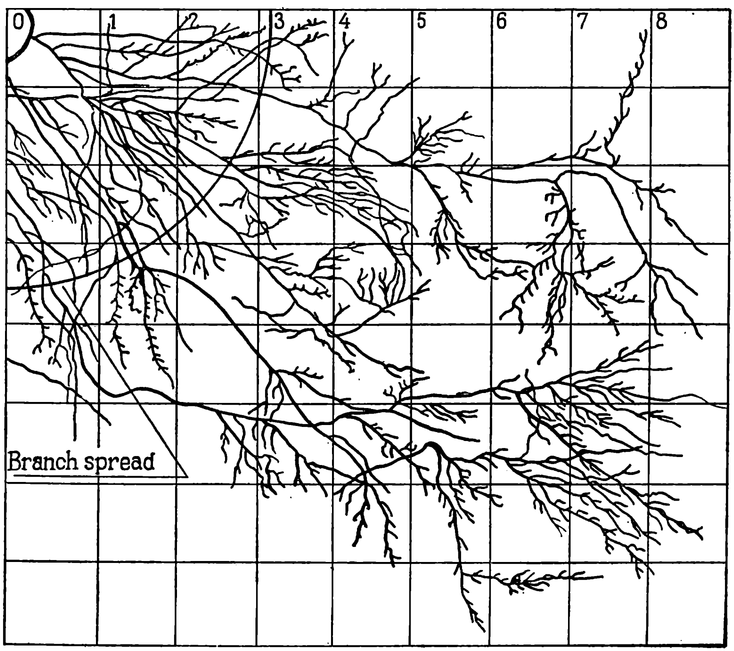


Fig. 25. A 45-year-old Sary Sinap apple on wild apple rootstock growing in the Crimea. The radius of branch spread is 3 to 5 m, the radius of root spread, 11 m

did not go deeper than 1.5 m. The roots of pear on vigorous rootstock penetrated 3.6 m deep and those of pear on quince rootstock, 1.6 m deep. In the Crimea, the roots of apple on Paradise apple and those of pear on quince extended to a depth of 4 to 5.5 m.

The number of vertical roots and their length may be considerable. For instance, the total length of all skeletal and fibrous roots on an excavated 45-year-old Sary Sinap apple (Chkalov state farm in the Crimea) was 2.7 km (1.6 km of vertical roots and 1.1 km of horizontal roots), 36 per cent of the roots (30 to 40 per cent in Kazakhstan) were under the branch spread and the remaining 64 per cent beyond it (in Georgia the respective figures were 38.9 and 61.1 per cent). In the Crimea such trees yielded 0.5 to 1 ton of fruit each annually (Fig. 25).

The bulk of the vertical roots of 18-year-old Olivier de Serr pear trees (on wild pear rootstock) growing in the heavy soils of northern Karakalpakia terminated at depths of 60 to 170 cm, and on light soils, at depths of 50 to 87 cm, while for some individual roots the respective figures were 3.1 m and 1.25 m (Dudkin, 1965). Under similar conditions the ends of most vertical roots of 15-year-old Rosmarine Blanche apple trees (on wild apple rootstock) were found at a depth of 40 to 70 cm, and some roots reached a depth of 1.2 m. In Semirenko Reinette, depth of vertical root penetration was 1.4 to 1.5 m (Matkarimov, 1965).

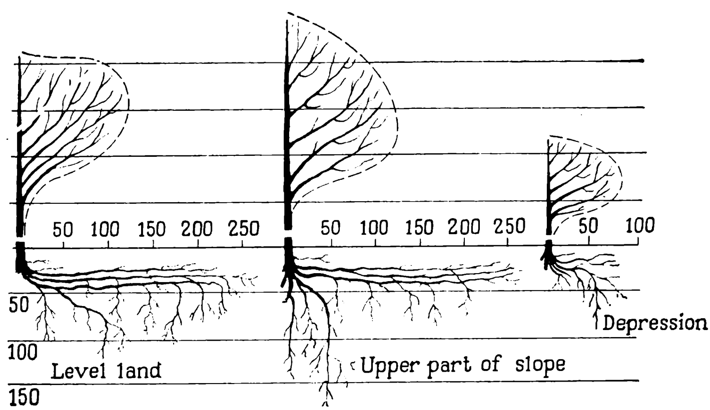


Fig. 26. Growth (cm) of above-ground part and root system of Vladimirskaya sour cherry in the Moscow Region (after Efimov)

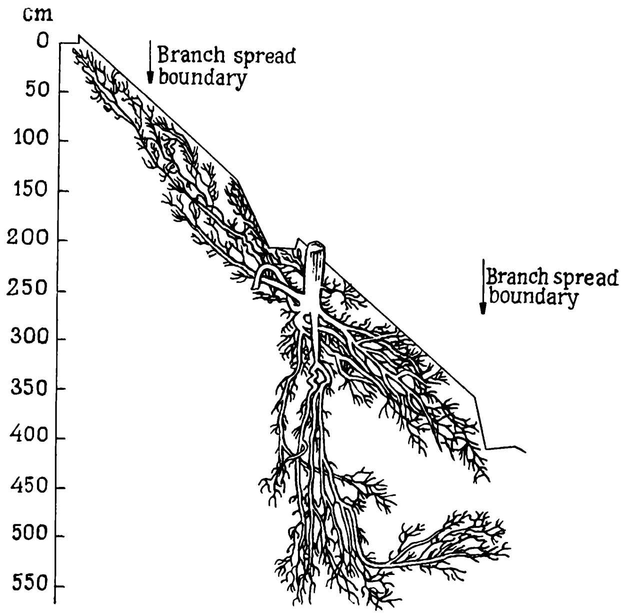


Fig. 27. The root system of a 16-year-old apricot tree growing on a terraced slope in a Kopet-Dag canyon (after Zapryagayeva, 1964)

In the soddy-podzolic soil of the Moscow Region the roots of apple descend 3 to 4.5 m deep, those of pear, plum, and sour cherry, 2 m deep. The main bulk of vertical roots in Antonovka Obyknovennaya apple (graft) extended to a depth of 1 m (on Chinese apple rootstock), 1.3 m (on Doucin III), 2 m (on wild apple and Anis seedling), and 2.5 m (on Antonovka seedling) (Ghena, 1957). The distribution of the root system of a plant growing on a slope differs from that of a plant growing on a plain (Fig. 26). An example is the root system of an apricot tree growing on a terraced slope in Tajikistan (Fig. 27, after Zapryagayeva, 1964). The roots usually extend downwards along worm burrows, those made by rain worms in particular, and along cracks in the soil.

In optimal environments the vertical roots of fruit plants descend as deep as 1 to 2 m in the northern zone, 2 to 4.5 m (Fig. 28) in the middle belt, 5 to 9.5 m in the southern zone (the Crimea, the Kuban area), and even 12 m (Kazakhstan).

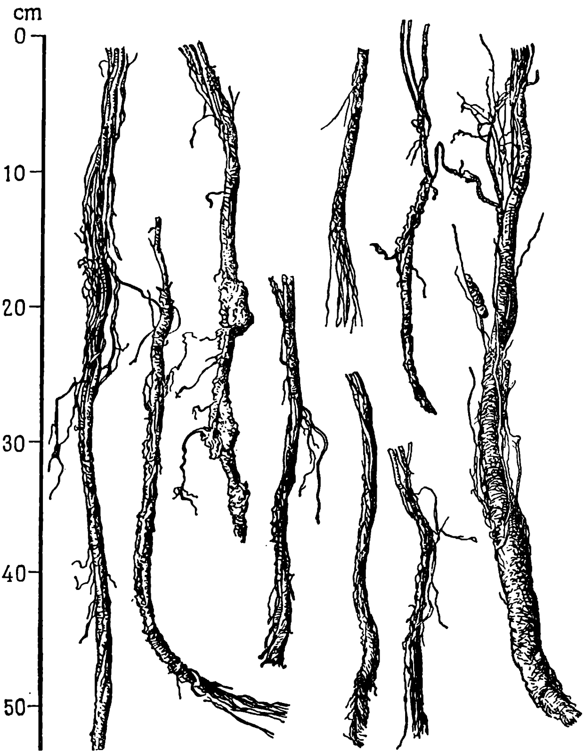


Fig. 28. Vertical roots of an apple tree (at a depth of 3 to 5 m)

In an orchard of an agricultural institute in the Crimea (Simferopol District) 35-year-old Sary Sinap apple trees, whose roots reached a depth of 4.6 m, yielded up to 300 kg of fruit per tree, while trees of the same variety and age growing in the same orchard but under different soil conditions (high water table) had roots growing only to a depth of 1.5 m and yielded only 100 kg of fruit.

Fruit trees with a powerful root system (spread wider and deeper) as a rule have a good appearance, are larger in size, live longer, are highly winter-resistant and yield a richer crop. Root growth in deeper horizons can be intensified in any soil, including soddy-podzolic, by deep ploughing, inter-row treatment, and fertilizing.

The best fruit-tree root system is that which is distributed not one-sidedly but evenly, along a circle, spreading deeper and wider, owing to which it can extract nutrients from a larger volume of soil and subsoil. Furthermore, a tree with such a system is more drought- and cold-resistant.

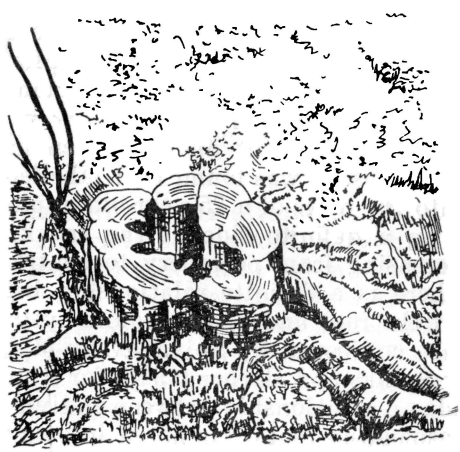
Correlation and Localization of Plant Life Activity

Correlation is the relationship between the structure and functions of parts of a plant organism, resulting from the adaptation of the organism to environmental conditions. Two types of correlation, *biomorphological* and *correlation of growth*, are usually encountered in plants (Beketovsky, 1959). Thus, the Sary Sinap and Candille Sinap apples are characterized by pyramidal crowns and by the elongated shape of their leaves, fruit and seeds (first type of correlation).

Correlation of growth in fruit plants was revealed long ago (second type of correlation): a tree with a vigorous root system has a vigorous above-ground system, and vice versa. There is also a correlation between half of the crown and half of the root system on the same side of a tree: to each skeletal root there corresponds a definite skeletal branch. This was pointed out by Schitt, who believed that as a fruit tree grows older its trunk may even split into several parts (Fig. 29) which are supplied by portions of the root system separated in a similar manner.

This provides evidence of another phenomenon—localization in fruit trees. It was found that labelled phosphorus introduced into the roots of a 25-year-old apple tree mainly accumulated in a definite side of the trunk, its amount markedly decreasing from periphery to centre (Evdokimova, 1955). There is a definite relationship between individual parts of the root and above-ground systems of a tree which was also confirmed by Spivakovsky (1958) for apple trees and by Spinks and Barber (1948) for coniferous seedlings in Canada. A relationship between individual branches and the corresponding roots was noted in own-rooted apple trees, but no clearly defined correlation was found in grafted trees (Belavin, 1956). It is also possible that grafted organisms do not exhibit such anatomical relationship between cells as that encountered in seedlings.

1



2

Fig. 29. Trunk of fruit trees separated into parts:

1—old pear tree in Uman (after P. Schitt); *2*—old apple tree in the Moscow Region (after Metlitsky)

The spring increase in phosphorus supply to the aboveground system of apple trees shows that it needs more phosphorus in spring than in autumn. But the root system requires more phosphorus in the autumn, which is confirmed by a greater phosphorus supply to the roots in that season. The rate of assimilation of labelled phosphorus in the first hours after fertilizers are applied is fairly high and may exceed 30-35 cm per hour in the spring, but in the autumn it is considerably lower. The movement of nutrients, particularly phosphorus, from branch to branch, however, takes place only when their concentration is much higher in some branches than in others (Kolesnikov and Palkevi, 1963, a).

The phenomena of localization and the domination of certain parts of a plant over others are not only of theoretical, but also of practical importance, especially in the implementation of agricultural measures (pruning, pinching, crop control, root care, etc.).

Vegetation and Rest Periods in Fruit Plants

Growth and development of fruit plants throughout the year are characterized by periodicity: a period of increased vital activity is followed by a period of relative rest.

We will discuss certain biological and biochemical features of fruit plants encountered during the two main prolonged periods of the yearly life cycle, the *period of vegetation* and the *period of rest*. To give a clearer idea of the life activity of fruit plants, Schitt (1958) distinguished also the *periods of transition* from vegetation to rest and from rest to vegetation.

Below we list the main features of all these periods.

The first period—the period of vegetative growth—is the longest with respect to the apparent changes occurring in a fruit tree: it blooms, becomes covered with leaves, forms flower and vegetative buds, and forms crops. Vigorous root growth takes place at the same time, particularly in spring and early summer.

A plant contains maximal amounts of starch and nitrogenous substances before vegetation starts, but they are almost entirely spent after active root and shoot growth and blooming (by mid-June in the middle belt of the Russian Federation), owing to which it is very important that in spring, i.e. by the time the first leaves form, the requir-

ed amount of active roots be already produced, so that a correlation is established between their activity and that of the leaves. Timely formation of active (absorbing) roots is facilitated by a good structure and adequate air and moisture conditions of the soil and appropriate nutrition. Sometimes, e.g., with excessive precipitation in the spring, a fruit grower has to take special measures (hoeing) to aerate and warm the soil so as to improve conditions for active root growth and increase the supply of water and nutrients to the leaves. In irrigated areas it is important to clean ditches and deepen their draining in order to lower the ground water table and so reduce the moisture content of the root-inhabited layer of the soil. It is not recommended to irrigate orchards during a wet spring.

From mid-summer, when tree growth is reduced or completed, but the leaves are still active (the process of assimilation continues) starch starts to accumulate intensely in shoots, spurs, and fruits. The shoots become woody. The activity of the root system decreases, sometimes considerably.

The second period is the period of transition of the above-ground portion of a plant to the hardening of tissues and winter stability. The lignification of tissues of the above-ground system terminates in this period. Sugars are converted to starch and, apparently, to fats. The accumulation of starch in the plant attains its autumn maximum. By the beginning of the third period (winter), particularly when conditions are favourable (irrigation and sufficiently high temperatures), most of the starch is converted to sugars, owing to which winter resistance of fruit trees increases. Vigorous growth of absorbing roots usually occurs during this period and continues till frosts set in.

The period of activity of the absorbing roots can be prolonged by employing appropriate cultural measures (manuring, mulching, snow retention, etc.) which contribute to the maintenance of the required temperature in the root-inhabited layer of the soil for a long period of time. In other words, the second maximum of nutrient accumulation in a fruit plant can be increased.

Owing to good autumn root growth the plant tissues are adequately supplied with moisture, which also improves winter resistance and increases resistance to desiccation. For these reasons moderate irrigation of orchards in au-

tumn, early winter and even mid-winter (in the south) is advisable.

Ursulenko's (1936) suggestions on the character of fruit tree care in the second half of the summer are important. He believed that the rest period is an adaptive reaction of plants to the unfavourable environmental conditions of the autumn-winter period. The change from growth to rest in fruit plants is an extremely important property acquired in the course of evolution. Once fruit trees are in a state of rest in the second half of the summer and cannot resume their growth, there is no reason for the apprehension that "increased moisture and good nutrition will renew growth and thus cause deficiency in the ripening of wood". However, owing to this apprehension many authors erroneously recommended lowering the level of management in orchards in the second half of the summer, particularly as regards the control of soil moisture.

In our opinion, after harvesting winter varieties, e.g. in the Moscow Region at the end of September, orchards should be fertilized and irrigated to ensure root growth in October and partly in November, i.e. till frosts set in.

Friedrich (1956) recommended watering orchards only before the frosts which is apparently advisable in the conditions of the GDR where the winter soil is warmer than in the Moscow Region.

The third period, the period of relative rest of fruit plants, is equally characteristic of the above- and underground parts of a tree. In the cool or cold winter months of this period starch almost completely disappears from plant tissues, being replaced by sugars and partly, perhaps, by fatty substances (Chandler, 1957). Considerable amounts of water and nutrients are already stored in the tree by this time. During warm winters in the south the roots are active, but in the middle belt root activity may continue into December or even later, in soil deeper than 40 cm, especially in deep horizons, owing to which the stores of water and organic substances are replenished to some extent. But during the entire period of relative rest moisture is continuously spent through the periderm of the stem and branches and through leaf scars and buds, particularly on the shoots. With strong winter winds fruit trees transpire considerable amounts of moisture, which may lead to withering of branches and even of the whole tree, particularly

after a dry autumn or with no irrigation applied. It is important that fruit plants be provided with adequate management (nutrition); the heavier the harvest obtained, the more thorough is the care needed. In droughty years the orchard must be irrigated during the vegetative period and in the autumn, and orchard shelters must be planted.

The fourth period, the period of transition from the winter state of relative rest to the spring-summer condition or vital plant activity, is characterized by poor growth (if any at all) of the absorbing roots with the above-ground portion of the tree starting vegetation. In this period the above-ground portion is supplied with water and nutrients stored in the fruit tree, particularly in the previous autumn. The more adequately a fruit tree was provided with water and nutrients in the autumn, the better it will grow in the spring. This shows the importance of the stored nutrients and water for the growth and development of fruit plants in the winter and early spring, and reveals the close relationship between the individual periods of the yearly life cycle of plants. Armed with the knowledge of these features of the vital activity of the above- and underground systems of fruit plants the fruit grower can influence it and obtain stable and heavy yields.

Meteorological and Soil Conditions of Studies

All the necessary meteorological data on precipitation, temperature of the atmosphere, soil temperature, early and late frosts, absolute minima and maxima of air and soil temperatures, thickness of snow cover, heavy frosts, etc. required for conducting an experiment are usually obtained from the nearest meteorological station. But the researcher should not confine himself to this information, he must carry out his own meteorological observations during the experiment.

Fruit plants are very "sensitive" indicators of soil properties. Kachinsky (1925) claimed that the soil "dictates" the plant root system the forms of its development. Knowing the properties of the soil, one can foretell the features of root development, and vice versa, the nature of the soil can be judged from the root system, all the more so since the roots take a very active part in soil formation. That is why it is necessary to describe the genetic horizons of the

soil and subsoils, study their mechanical and chemical composition, the total amount of humus per horizon, absorbing capacity, the structure and physical properties of the soil, soil moisture during a growth period, capillary moisture capacity, porosity, aeration, degree of saturation of the soil with water, and to determine the depth of the ground waters (water table) and their chemical composition.

Soil conditions, the arrangement of genetic horizons in particular, greatly influence the distribution of both horizontal and vertical roots. That is why in root studies it is extremely important to record the arrangement of genetic horizons on a drawing along with the distribution of the root system. In this connection the suggestions made by Gruzdev in 1966 are of great interest. He conducted all his experiments in close cooperation with the Pomology Department of the Timiryazev Academy and always reflected the diverse relationship between soil conditions and the root system of fruit plants. Given below (with some minor alterations) are Gruzdev's findings on this problem.

The process of soil formation in nature has continued for thousands of years. The factors characterizing the subsoils are classified as those that remain stable for a long time, those that change very slowly, and those that are unstable and change rapidly. Taking this into account, land for growing orchard plants can be chosen more rationally.

The science of genetic soil formation, which studies soil formation processes occurring as a result of interaction between the rock and the biosphere (microorganisms, flora and fauna), distinguishes the following eight persistent stable factors which characterize the subsoils.

1. *Genetic soil horizons* in the subsoil profile are a steady indicator of numerous everyday quantitative changes which we do not notice during the process of soil formation but easily distinguish when they transform to qualitative ones. The surface rock, named parent rock, undergoes changes as a result of soil processes, forming genetic soil horizons. Hence, each horizon has its own history and capacity measured in centimetres.

The following horizons are distinguished in the subsoil profile 2 to 2.5 m deep: humus-accumulative horizon A_1, podzolized (bleached) horizon A_2, illuvial horizon B, parent rock C, and sometimes bedrock D if it is penetrated by the

roots of fruit plants. Each horizon of the profile can be divided into subhorizons (for instance, B_1, B_2, B_3).

The indicated genetic soil horizons and subhorizons in the subsoil profile are a sort of "separate rooms of a flat" in which we lodge our plant. Their quality is first of all demonstrated by the planted tree itself, by the character of its development and the condition of its roots.

All the other factors, listed below, both the persistantly stable and the rapidly changing ones, are discussed according to the genetic soil and subsoil horizons, which makes it possible to determine their "inner" changes with the profile depth, while their combination in each individual horizon allows us to judge whether its conditions are favourable or unfavourable for the vital activities of the root system. A knowledge of conditions in each horizon and of the peculiarities of the plant itself helps in each individual case to establish the factors responsible for the degree of development and the condition of the roots of fruit plants, to foresee their further activities, and to recommend an optimum combination of soil treatment techniques.

2. *The natural structural composition of soil horizons*, which also develops slowly in the process of soil formation. It affects the conditions of vital root activity; as a result they may be either quite favourable (with a granular structure of chernozem soils), or fairly favourable (with a crumbly, nutty structure), or unfavourable (with a dusty, lumpy, column structure). Incorrect tillage of soil worsens its natural structure and vital conditions of plants.

3. In the process of soil formation so-called *new formations* (ortstein grains, lime concretions, faded salts, gley soil, etc.) form in the soil horizons. Their presence and the degree of their manifestation in different soil horizons allow one to characterize the subsoil profile from the agricultural point of view in relation to fruit plants.

4. *The mechanical composition of the parent rock* and the slowly changing mechanical composition of genetic soil horizons. The conventional determination of the mechanical composition by the content of "physical clay" (to within 5-10 per cent) can be used for agricultural evaluation of soils for orchard plants too. But changes in the mechanical composition of the different subsoil genetic horizons, which are more important, are estimated with the aid of more accurate and finer mechanical analysis, which makes it

possible to determine the content of oozy and colloid components in it.

A number of physical properties of the subsoil profile, extremely important for the development of the root system, are determined from its mechanical composition.

5. *Air and water conditions*, determined by Tyuremnov's or Golubev's method according to the colour of samples taken from each genetic horizon. Diagrams are plotted showing the darkening of the tint, a rich tint, and a moderate tint. They help to establish whether certain air and water conditions are favourable, satisfactory or unfit for this or that fruit species.

This index characterizes a combination of natural conditions: a darkened tint shows the isohumus curve of the profile, a rich tint, the displacement of ferric sesquioxides along the profile, while a moderate tint shows the presence of ferrous oxides which is an indication of an anaerobic process, i.e., of the degree of profile aeration.

6. *The compactness of soil horizons*, which is measured with a Golubev or Kachinsky densimeter, gives a clear idea of the conditions for vertical and horizontal root spread of fruit plants. Numerous densimeter readings obtained in the course of many years make it possible to determine the degree of compaction, i.e. favourable, satisfactory, or poor.

7. *The depth and degree of effervescence* indicate the extent of soil leaching, characterize the air and water conditions, show the lack of moistening and the presence of alkaline reaction of the soil solution.

8. *The general appearance of the soil profile* is a schematic representation of all genetic soil horizons, their ratio, the character of transitions from one horizon to another, clearly defined new formations, mole-tracks, prevailing direction of cracks, root spread, and other features.

Besides the eight stable factors mentioned above, there are several rapidly changing features, which are also of high importance for agronomical characteristics of the soil profile.

Although soil moisture along the genetic horizons at the moment of investigation is a rapidly varying index, nevertheless it provides very valuable information with respect to the different soil horizons. Thus, when dry areas are formed in the soil, hundreds of thousands of root hairs are isolated from the process of vital activity, while in the

above-ground part heavy shedding of young fruit and leaves occurs. An excess of stagnant top water in intermediate horizons of the soil profile causes the death of young fibrous roots, chlorosis of the foliage and arrests the general development of the apple tree.

According to the degree of moisture soil horizons are classified as follows:

(1) *dry*; when soil is destroyed dust forms; such soil contains no water physiologically assimilable by the plants;

(2) *fresh*; when the soil is destroyed it crumbles but gives no dust, its reserve of physiologically assimilable water is negligible (1 to 2 per cent);

(3) *moist*; when the soil is destroyed it clings, it contains a full supply of physiologically assimilable water;

(4) *wet*; when the soil is destroyed drops of water are produced; such soil is excessively moist and lacks air.

The temperature of the soil profile along the genetic soil horizons, which depends on the annual temperature variations in the surface air stratum and on the depth in the soil profile, gives an idea of the heat regime, which greatly influences the vital activities of a fruit plant. A gradual temperature variation with depth is often disturbed by an abrupt change, which produces an unfavourable effect on the plant. The way a heat wave spreads to the deeper layers of the soil in the summer and the process of its fading in the autumn must be taken into account when planning soil treatment and plant management.

Given below are some experimental data obtained in studying the soil conditions under which the root system of fruit plants develops (see Tables 10 to 13).

Tyulin (1958) emphasized long ago the necessity of studying the interaction of colloid parts of the soil with living cells of hair roots of plants. The idea was expounded in his recent works and reflected in investigations of other authors. Noskova (1961) found that a close contact of absorbing roots with fine dusty particles of clay exerted a favourable effect on the growth of vegetative organs of lemon seedlings, and attributed it to increased activity of exchange ion adsorption from the soil. The Japanese fruit growers Kurokami, Asidzava, and Kuretani (1954) added silt containing 4.1 per cent gravel and 71.1 per cent silt particles taken from the bottom of a pond, to soils containing 19.4 per cent rubble and 36.7 per cent silt particles.

Table 10

Development of Root System in Relation to Compaction and State of Soil (after Vashchenko, 1962)

Readings of densimeter, kg/cm²	Soil state	Behaviour of the root system of fruit plants
0-10	Loose	The roots spread unhindered in all directions
10-20	Loosely packed	The roots spread freely in all directions
20-30	Slightly compacted	The roots penetrate in all directions
30-60	Compact	The roots encounter obstacles. The amount of roots is usually reduced almost by half
60-100	Heavily compacted	The roots penetrate only along cracks

Table 11

Development of Root System of Fruit Plants and Grapes on Chernozem-Like Sandy Soils According to Genetic Horizons in Relation to the Strength and Density of the Soil (after Vashchenko, 1962)

Strength, kg/cm²	Density, g/cm³	Soil condition	Aeolian deposit and genetic horizon of soil and subsoil (loam)	Root spread
1	2	3	4	5
1.3-1.4	0-7	Very loose	Aeolian deposit of fairly humic sand (contemporary) and tillable layers of sandy soils	Unhindered
1.4	7-12	Loose	Horizon A	ditto
1.4-1.5	12-22	Slightly loose	Horizons A, B_1, and C with thin ortsands	ditto
1.5	22-35	Slightly compact	Horizons A, B_1, B_2, C	ditto
1.5-1.6	35-60	Rather compact	Horizons A, B_1, B_2, C	Slightly hindered
1.6	60-70	Compact	Horizons B_2 and B_K, ortsands in horizon C	Hindered

Strength, kg/cm²	Density, g/cm³	Soil condition	Aeolian deposit and genetic horizon of soil and subsoil (loam)	Root spread
1	2	3	4	5
1.6-1.8	70-100	Very compact	Horizons B_K and D, powerful ortsands, caked dry carbonate sands of horizon C	Only along shrew burrows, old rhizome passages and cracks
1.7-1.9	100	Extremely compact	Massive layers of ortsands	ditto

Table 12

Mechanical Composition (%) of Light Soil of Pear Plantations in State Farm "Kommunism" (after Dudkin, 1965)

Horizon	Sampling depth, cm	Hygroscopic humidity, %	Fractions of fine soil: sand: coarse and medium (1-0.25 mm)	sand: fine (0.25-0.05 mm)	coarse dust (0.05-0.01 mm)	clay: medium dust (0.01-0.005 mm)	clay: fine dust (0.005-0.001 mm)	clay: silt (0.001 mm)	clay: total clay (0.01 mm)	According to Kachinsky's classification
A_1	0-20	1.15	—	—	40.93	9.86 and so on	10.30	10.74	30.90	Medium loam

Table 13

Agrochemical Composition of Light Soil of Pear Plantations in State Farm "Kommunism"

Horizon	Sampling depth, cm	Humus (after Tyurin), %	Total nitrogen, %	Movable P_2O_5 (after Machigin), mg-eq	K_2O (after Protasov) mg-eq	Absorbed bases, mg-eq: Ca	Absorbed bases, mg-eq: Na	Absorbed bases, mg-eq: Total bases	Soluble Na, mg-eq	Dry residue of water extract, %	Water-soluble humus, %	pH of salt extract	pH of water extract
A_1	0-20	1.40	0.090	2.41	60.0	32.50	4.50	37.0	22.2	2.693	0.010	9.0	9.0
						and so on							

As a result, soil fertility improved and the growth of peaches, grapes and soy-beans was much better.

An important factor is the moisture content of the soil. Studies at the Field Experimental Station of the Timiryazev Agricultural Academy (Doyarenko, 1926) showed that the content of unavailable soil water amounted to 10 per cent. In summer a dry layer can be encountered under growing plants at a depth of 40 to 70 cm (soil humidity 6.79 per cent), which produces a harmful effect on the growth and development of plants. This clearly shows that deep roots play an important role in the water supply, and it is essential that moisture and roots easily penetrate the subsoil.

Growth and Fruiting Control

A powerful root system (its wide and deep distribution in the soil) and a persistent and adequate annual growth of absorbing roots are the principal prerequisites of abundant fruit bearing. One of the main factors contributing to the formation of a powerful root system is a rational choice of the best soils for orchards. Fruit trees must be planted after a deep plantage ploughing with organic and mineral fertilizers introduced.

By observing regularly the vital activity of fruit trees and revealing the true causes of particular changes in their growth and development, a fruit grower can always take opportune measures and prevent any unexpected pathological phenomena. Even now, fruit growers often have to resort to urgent measures after a pathological phenomenon has already manifested itself and must be eliminated without delay. The main task in such cases is to determine the cause of the phenomenon quickly and correctly. It is still more important to prevent plant diseases by efficient orchard care.

The development of the root system should be examined at least once in 5 to 10 years in one or two trees by removing a 20- to 30-cm layer of soil from one-third of the space under each plant. As a result, the following features can be determined: the depth of rooting and root thickness, the size and spread of the root system with relation to the size of the branch spread and interrow spaces, the area occupied by the root system, and the depth of ploughing and its effect on the healing of injured thick roots.

It is advisable to excavate, every season, an area of 1 sq m on the periphery of the branch spread to the depth of the bulk of root spread, particularly in irrigated zones and throughout the whole plot in orchards with a high ground-water table. Such a measure will help to examine the condition of the root system regularly.

The development of the root system can be judged at any time of the year from the colour of the root cortex. The poorer the water-and-air conditions of the soil, the darker will be the brown colour of the roots. If the soil is kept overmoistened for a long time, particularly in summer, or is bogged up, the roots turn black with a blue tinge and then perish, while the cortex separates from the wood.

It is necessary to conduct monthly observations of the root growth periods by digging the soil to a depth of 10 to 40 cm in order to fix the right time for carrying out the appropriate agricultural measures in the orchard (irrigation, fertilizing, ploughing, etc.) with due consideration for their effect on the root system of the fruit trees.

The development of the above-ground organs of the trees, shoot growth, and the development of leaves must be watched as carefully. Deterioration of the conditions of root activity causes warping of leaf blades, early leaf fall, cessation of shoot growth, and reduced crops in later years.

All the necessary prevention measures, pest control, and disease treatment must be carried out without fail. This is, in the first place, essential for keeping the leaves alive and promoting the normal functioning of the foliage (supplying the root system with carbohydrates) which controls the growth and vital activity of the roots and, in the long run, the growth and cropping of the fruit tree.

Harvests can be considerably increased by changing and improving the methods of plant care. To do this, the fruit grower-researcher must be familiar enough with the root system; therefore, first of all he must master the methods of studying the root system of fruit plants.

The studies of the root system should be combined with soil, agrochemical, physiological and other related researches. This will make the studies more comprehensive and guarantee more reliable results. The findings of such integrated studies will provide a more correct theoretical background for the control of root growth in fruit plants.

Control of the growth and development of the root and above-ground systems of fruit plants will allow the growers to develop within a short time adequate techniques of differentiated soil treatment for each fruit-growing zone and thus obtain high annual crops in the orchards.

CHAPTER 2

DEVELOPMENT AND CLASSIFICATION OF METHODS OF ROOT SYSTEM STUDIES

Studies of root systems, at first those of herbaceous plants and then of forest trees, were started long ago. The first to describe the morphology of the root system was Hales (1727), who, among other things, determined the surface area of roots from their total mass. The early research dealing with the techniques of root examination was elucidated in reports containing brief descriptions of a particular method. Among them we may list the works of foreign researchers Nobbe (1875), Müntz and Jirard (1891), Dehirain (1893), and King (1893), and those of Russian investigators Gulbe (1888), Tanfilyev (1894), Slyozkin (1893), Dokuchayev (1900), Sokolovsky (1898), Tolsky (1905), and Rotmistrov (1907).

Investigations concerned with the root systems of herbaceous plants and the research procedure were done on a wider scale by Cannon (1911), Modestov (1916), Miller (1916), and Weaver (1926).

Publications on methods for the examination of the root system of fruit plants began to appear only at the close of the last century.*

The various methods for studying the root system as a whole promote understanding of the role it plays in the plant's life, of its morphology, anatomy, physiology, biochemistry, its interrelation with the above-ground part, its participation in photosynthesis, nutrition, fruiting, etc. Botanists, physiologists, and biochemists use available methods for solving these problems.

The principal aim of studying the root system of fruit plants is to develop differentiated soil treatment and plant

* We shall dwell on these publications in more detail when describing each particular method.

management ensuring high annual crops. Root studies cover a wide range of particular problems. For instance, it is important to know the capacity and distribution of skeletal, fibrous and especially absorbing roots in different soil horizons, the dynamics of the growth of absorbing roots in relation to environmental factors, the dimensions and projections of the root system and crown of a plant, the stand-thickness of roots in different soil horizons, the distribution of fibrous roots according to the age periods of a plant, the dynamics of their displacement from the trunk to the periphery, the manner in which the root systems of one and the same species or of different ones intertwine or, on the contrary, repel one another (as was revealed in peach and persimmon), and the nature of distribution of vertical roots in soil and subsoil. All the information must be expressed in numerical values and illustrated by diagrams, drawings, and photographs.

In investigating the structure and vital activity of the root system the researcher is faced with many problems whose solution requires appropriate methods aimed at obtaining correct and reliable results. The British root researcher Rogers (1932) and the American root investigator Weaver (1926) believe that there are no simple methods of studying the root system. Beideman (1938) stressed that laboratory studies of the root system must be done with the same accuracy and care as the mechanical analysis of soil. Only then can reliable results be obtained.

Special features of root excavation. The root system, especially that of trees, is usually deeply hidden in the soil and occupies considerable space. That is why both visual observation of the roots and their excavation from the soil are difficult. To solve many questions it is necessary to study the root system throughout the whole (or at least the main) depth of rooting which in fruit trees often amounts to several metres. Thus, the horizontal roots of cropping apple trees on our experimental plot in the Crimea occupied an area 22 m in diameter, while the vertical roots of a sweet cherry tree in the Kuban Region penetrated down to a depth of 9.5 m.

Root excavation is often an extremely laborious and tedious task; besides, it is important not to lose fibrous roots, especially the absorbing ones: they are the most brittle part of the root system. The different problems in-

vestigated require different methods for their solution, but one thing is clear: the researcher must very carefully choose, or even work out, a technique best suited for the purposes of the investigation and most practicable.

Many valuable methods for studying the root system of various herbaceous and tree plants have been developed during the past hundred years. But fruit growing is continuously faced with new problems, so that there is an urgent need for the development of new methods, more accurate, efficient and reliable, and for the improvement of the existing ones.

Classification of Methods

Investigation of the root system is a very complicated task due to the great diversity of fruit plants, of their longevity, widely differing soil conditions, different management, the necessity of studying the whole plant, and sometimes only some aspects, as for instance, the dynamics of root growth, the depth of rooting for horizontal roots, etc. Some problems have to be studied in field conditions, for example on vast areas for selecting new orchard plots or for quick detection of the causes of early leaf shedding in the spring, of the shrinkage of tree tops, of rosetting or chlorosis of leaves, and of other adverse phenomena usually associated with the vital activities of the root system.

In some cases a detailed, often extremely labour-consuming method, and in others somewhat "simplified" but rapid methods of studying the root system have to be employed. Sometimes it is important to observe the daily root growth directly, either through a glass pane or in specially constructed root cabins in order to reveal the response of a plant to changes in certain natural or agricultural conditions. A special method is employed for this.

A wide range of valuable information on the methods of studying the root system of various plants has been accumulated. Many of them can be used successfully for studying the root system of fruit plants.

Fruit growers have proposed new original methods taking into account the specific features of fruit trees, namely, their size, mutual relations between the rootstock and scion, and the large dimensions of the root system.

The first attempts to classify the methods of examining

the root system of various plants were made long ago. For instance, Kachinsky (1925) suggested the following classification:

(1) study of roots grown in water cultures;

(2) study of roots grown in boxes and lysimeters which are either filled with loose soil or have a block of soil of the same size put in them; before they are examined the roots are washed out;

(3) study of roots grown in natural conditions, involving their excavation and washing;

(4) study of roots grown in natural conditions, involving observation of the growth of some of the roots from special pits;

(5) study of roots by washing them with a jet of water out of a soil face cut on natural slopes and artificial banks;

(6) study of roots by excavation along their passages.

Vishnevsky (1936) proposed that all the methods be divided into three groups according to the nature of the procedures used: (1) methods of washing out; (2) methods of excavation, and (3) methods of stationary studies.

Taranovskaya (1957) worked out a rather complicated classification based on differences in details of individual procedures. With some insignificant omissions, this classification may be presented as follows:

Group I. *Methods of studying root systems growing in natural conditions*:

(1) isolation of root systems for static studies of their morphology;

(2) stationary observations of the dynamics of root growth;

(3) record of weight distribution of root mass in soil layers;

(4) determination of the extent of contact between the root systems and the soil and the size of their "active portion";

(5) direct determination of the physiological activity and power of root systems by the rate of "plant weeping".

Group II. *Methods of studying root systems growing in a limited space* (boxes, vessels, lysimeters, etc.):

(1) studies of the morphological features of root systems in individual varieties of plants and their kinds when grown in boxes;

(2) observation of the dynamics of root growth;

(3) studies of the dependence of the development of root systems on the composition and properties of the nutrient medium (water cultures, etc.).

Group III. *Methods of laboratory studies of the chemical composition, physiological functions, synthetic activity of the roots, etc.*

We recommend a somewhat simpler classification in studying fruit plants. The number of methods for investigating the root system of herbaceous and tree plants has been rapidly increasing in recent years, which makes it difficult to work out a clearer and more convincing classification. Furthermore, the technique of studying many elements of the root system has not yet been developed fully and is debatable.

We base our studies mainly on the morphological and physiological differences between the root systems of fruit plants, and for the present apply the following four basic methods:

(1) the skeleton method,
(2) the monolith method,
(3) the stationary method,
(4) the laboratory methods.

With certain reservations the soil face method and the trench method may be included in the skeleton method, and the methods of free monolith, samples, and boring in the monolith method. One method is frequently supplemented with another. The different and similar features of these methods will be pointed out where each individual method is discussed. It should also be borne in mind that almost every one of these methods has undergone a number of important changes, being rationally supplemented and modified.

CHAPTER 3

THE SKELETON METHOD

Specific Features and Application

This method consists in uncovering the whole root system by dry excavation, digging along the course followed by the roots in the soil and subsoil and then drawing a plan of the system on paper.

It is one of the oldest methods for studying the root system of plants. As far back as 1727 Hales applied it successfully in his attempt to trace the distribution of the root system and determine the effect of the soil and moisture on root growth. Later is was used by many scientists, especially by Weaver (1919) and Kazakevich (1925), who examined the root system of herbaceous plants and forest trees.

Complete uncovering of the whole root system gives a fairly accurate idea of the spread and distribution of horizontal and vertical roots, their length, depth and thickness. Such efficiency can hardly be achieved by employing the usual methods of washing, since it is difficult to retain the roots, especially fine ones (fibrous nets), in their natural position and prevent their loss with water (Krasovskaya, 1925).

The skeleton method is the only method which enables the researcher to get a clear picture of the structure of the root system of fruit trees, the depth and width of rooting and to use without undue delay the information in working out measures and techniques relating to soil treatment. That is why it is now applied not only by field-crop cultivators and sylviculturists, but by fruit growers as well. In the earlier studies the skeleton method was used by Bailey (1895), Goff (1897), Burril and Blair (1898) in the USA, Pickering (1909) in England, Goethe (1909) in Germany, Kvaratskhelia (since 1905), Schitt (since 1913), Solyanikov (since 1920), and V. A. Kolesnikov (since 1920) in Russia.

This method is used in three types of research:

(1) for a more detailed study of the root system, its morphology, structure, and distribution in the soil; (2) in field surveys, when it is necessary to reveal the peculiarities of growth and yield of fruit plants over vast areas, including the depth of rooting, in order to establish more precisely whether the soil is fit for orchard growing; (3) with some simplifications, in systematic investigations undertaken for the control of soil-treatment measures in orchards.

The skeleton method makes it possible:

(1) to obtain a clear idea of the vigour of the root system and its distribution in the soil and subsoil;

(2) to determine the ratio of the root spread diameter to the branch spread diameter, the depth of rooting for both the bulk of the horizontal roots and separate roots;

(3) to get a clear picture of the architectonics of the root system according to species, rootstock, variety, and age of the plant, to genetic soil horizons, the ground water table, compacted interlayers and inclusions in the soil, and soil treatment;

(4) to determine visually the location and amount of skeletal, semiskeletal, and fibrous roots; the skeleton method is unsuitable for recording the weight of most of the fibrous roots, especially absorbing ones, since they dry very quickly and often break in the course of uncovering;

(5) to trace the behaviour of roots when they meet other roots of the same tree, or the roots of another tree of the same or different species; to determine the colour and number of lenticels on the roots which characterizes the state of the root health; to detect cracks in the soil, and determine the number and size of worm burrows (those of rain worms in particular) used by the roots;

(6) to establish the mutual relations and interdependence of the root system and the above-ground part of a fruit tree as regards their size and spacing over the orchard area, and the effect of orchard treatment such as soil management, irrigation, fertilizing, and plant trimming.

But not all problems can be solved using the skeleton method. In a number of cases, as will be shown later on, it must be replaced by, or combined with, other methods. On the whole, the skeleton method is extremely valuable and applicable in solving many theoretical and practical problems of fruit growing.

Techniques of Root Excavation

We used the skeleton method for the first time in 1925 in the Crimea and later in the Kuban area and the Moscow Region for excavation of the entire root system of fruit trees by uncovering both horizontal and vertical roots.

It is very important to know how the two different types of roots are shown on a plan with their spread in the lateral and downward directions.

Preparations for work and the excavation itself are carried out as follows.

First, high-quality drawing paper is prepared and secured to a plywood board for convenience. Depending on the diameter of the root spread (which is about one-and-a-half times that of the branch spread) a 1:10, 1:20 or even smaller scale is chosen. If a 1:10 scale is accepted, the sheet of paper is divided into 2.5-cm squares, which correspond to 25-cm squares on the soil surface. Thus, the area of the paper and plywood board may vary in accordance with the area to be excavated.

Then a typical tree is selected in the manner described above, and the horizontal projection of the branch spread and the irrigation hole (if such holes are used) is drawn on the plan; the four cardinal points are marked and the horizontal projections of the branch spread of the neighbouring trees (if they are aged) are drawn, since the roots of the tree studied may spread beyond them (or, conversely, they may avoid meeting the roots of other trees of the same or different species).

The horizontal roots are usually drawn on one sheet of paper and the vertical roots, on another sheet divided into small squares in the same scale as the first one. But sometimes some space is left on the margins of the first sheet after all the horizontal roots are drawn, and all the verical roots or part of them can be plotted on the same sheet (in such cases one sheet may suffice).

Before excavation is started a circle of diameter about one-and-a-half times that of the horizontal projection of the branch spread is marked round the tree chosen for investigation, and its surface is thoroughly evened out. To remove the earth evenly and facilitate recording of the root depths on the drawing, 20 to 30 small wooden planks 3-5 cm by 50-70 cm each with scale divisions of 5 to 10 cm are

driven into the soil of the encircled area flush with the ground.

The upper layers of the soil my be removed with a shovel, until the first fibrous roots, usually fine nets, are exposed. Depending on soil conditions, species, variety, rootstock and soil management a considerable surface layer of the soil (15 to 30 cm and deeper) may prove to be free of fibrous roots. For instance, in droughty areas with a system of bare fallow the roots of such species as apple, pear, and some others are distributed deeper in the soil, whereas in damp areas and in a soil with a sod-humus system or seeding of perennial grasses the roots of apple trees and particularly those of plum and sour cherry exhibit shallow distribution.

The soil should be removed with a shovel very carefully, beginning with a small area, so as to facilitate further orientation when uncovering the roots throughout the whole area of their distribution.

Excavation is begun from the trunk, removing the soil gradually, layer by layer, until the first roots (usually fine ones) are exposed. It must be borne in mind that the further are the roots from the trunk, the deeper they extend into the soil. This is true for any environmental conditions and for any species.

Once the fibrous roots are exposed, they are unearthed very carefully throughout the whole area, using small scoops, special two- or three-pin metal forks, chisels, and awls. The earth is removed with small scoops or simply by hand and thrown outside the marked circle. It is important to free the roots from the soil if the studies require recording of their weight.

In investigation of herbaceous plants Lavrenko (1947) removed the soil mostly with his hands, without using any scoops or shovels, and then cleaned the roots with a large brush. This method is still more suitable for the excavation of fruit plants, whose roots are much stronger.

With the aid of wooden planks driven into the ground the earth is removed evenly from the whole surface of the circle, thus ensuring an even ground level, which helps to keep the exposed roots intact and to prevent them from being broken or displaced from the actual depths of distribution and direction of growth. In this manner a true plan of the roots can be made.

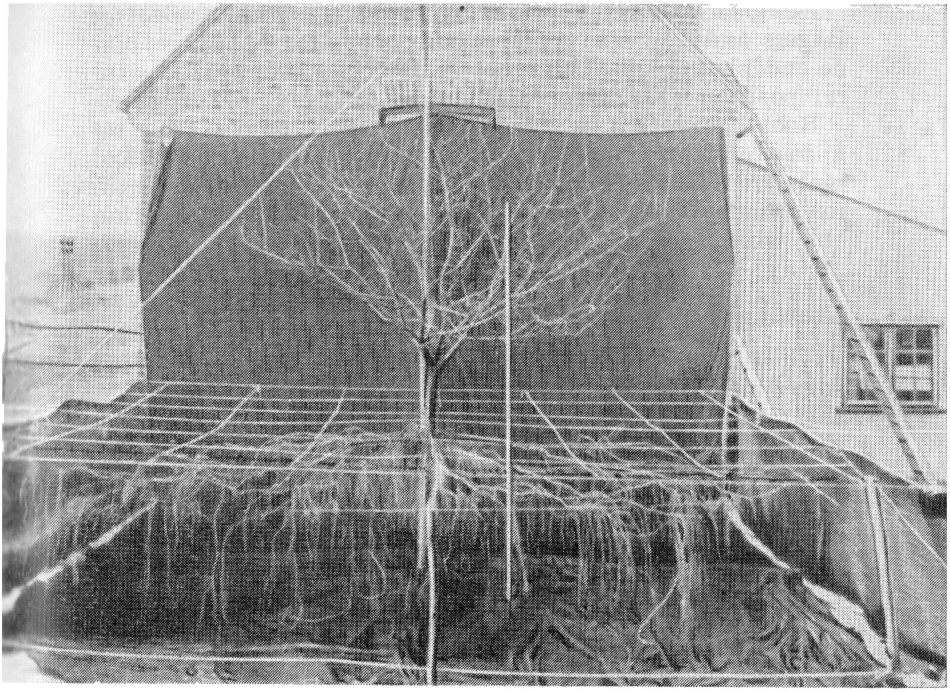


Fig. 30. Lane's Prince Albert apple on rootstock No.1. General view of the tree with the excavated root system (after Rogers, England)

In Italy Breviglieri (1953) improved the skeleton method by introducing a horizontal net (0.5×0.5 or 1×1 m mesh) made of rope or wire which was stretched taut at the soil level after the first horizontal roots were exposed. Then he drew the roots on the plan and continued to excavate the whole root system in the same way by repeatedly applying the net to the newly uncovered roots. This made the work easier and ensured the accuracy of the drawing. Furthermore, he installed a metal frame directly above the string net to support a platform with a ladder for the observer. Sometimes he used water to wash out the required portion of fibrous roots in a certain sector or place. To keep the tree in a stable position he used special props for the skeletal branches and roots. For convenience of filming and drawing, roots were frequently held in their natural position.

On excavating the whole root system of an apple tree Rogers and Vyvyan (1934) secured the tree firmly in place and photographed the root system in a practically natural position (Fig. 30).

Root excavation is a labour-consuming process and requires patience and skill. The horizontal and vertical roots are exposed gradually. They have their specific features, which must be taken into account during excavation and when they are drawn on the plan.

Drawing a Plan of Horizontal Roots

These roots are commonly found 30 to 75 cm deep, but sometimes at a depth of 1 m and even deeper, especially in the southern areas. Arising from the stem (rootstock) base the horizontal roots lie in great numbers at different levels, one above another, in the soil and subsoil.

The uncovered roots are shown as lines on the plan to a chosen scale (Fig. 31). All bends or deviations are designated conventionally by a fraction, the numerator showing the root thickness (mm), and the denominator, the depth of penetration (cm). On a final plan of all horizontal roots or when they are redrawn on another plan the root thickness is shown to scale, i.e. the roots are represented by lines of different thicknesses. In this case only the denominators are left (showing only the depth of root penetration).

If an experimenter requires a more vivid picture of the morphological features and arrangement of fibrous roots, they are drawn on another sheet of paper to a larger scale or even full size. Sometimes this has to be done because it is not always easy to photograph fibrous nets.

Using the method described, horizontal roots found in deeper layers are gradually uncovered and drawn on the plan to the chosen scale. When exposing horizontal roots lying in deeper horizons, where the soil may be dry or compact, the latter should be moistened overnight so that the water can penetrate to a depth of 1 to 2 m. This will greatly facilitate further excavations, and will help to keep the roots, particularly the fibrous ones, intact.

As the horizontal roots are unearthed they are usually tied to tree branches, otherwise they will interfere with the work, or, if the whole root system is excavated, they are gradually cut to their stem.

When excavating the roots of a tree, roots of neighbouring trees of the same, and sometimes of a different species may be encountered. It is good practice to draw them on the plan (to the same scale), but using a different colour to get a more vivid picture.

It is also desirable to show on the same plan (or on a separate sheet of paper) the arrangement of roots (depth, amount, and mutual positions in the soil) of plants seeded, planted, or naturally growing on inter-row spaces of the orchard (within the zone of the root excavation).

Drawing a Plan of Vertical Roots

Most of the vertical roots branch off horizontal ones. That is why, after a horizontal root has been recorded on the plan, it is cut off from the vertical root, and the place on the plan is marked with a circle in the centre of which a number is placed corresponding to the number on the slanting soil face left for excavating the vertical root. If the root diameter is small a label bearing the appropriate number is attached to the spot from which the root was removed. After all horizontal roots are exposed and removed only the upper ends of the vertical roots are seen on the surface of the marked circle; on the plan they are indicated as small circles with numbers.

If there are a great number of vertical roots, they are gradually exposed in the manner described above by removing the soil, and drawn on the first plan (on the margins) or on another sheet of paper. To excavate all the roots more easily and quickly, a deep trench may be dug on one side, close to the roots, for dumping the removed soil. If the soil is dry and compact it should be moistened with water in the same way as was done in excavation of the horizontal roots.

The frame described above helps to represent the vertical roots on the plan. In the process of uncovering they can be systematically photographed (2 or 3 times and more), first staining them with lime to make the films more distinct. On the plan, at the beginning of each root the root thickness is shown in millimetres.

Roots running in all directions must be excavated and represented on the plan very carefully in order to obtain a

more accurate and reliable picture of the distribution of the root system throughout the soil and subsoil horizons.

Additional Observations

It is advisable to keep daily records of the specific features of roots which cannot be shown on the plan, for instance, the propagation of roots along worm burrows or along dead roots of trees or grasses. In such cases it is important to record the number of burrows per 1 square metre and their diameters, for each 50 to 100 cm of depth, for soil cracks, etc. An example of such a record sheet is given in Table 14.

Table 14

Species	Depth, cm	Number of worm burrows per 1 m^2	Percentage of burrows with a diameter of			Total
			1-5 mm	6-10 mm	11-20 mm	
Peach	50	248	57	42	1	100
		and so on				

In the course of excavation, samples of the roots should be collected and records made of the nature of injuries caused to them (by implements, pests, diseases), of cases of root regeneration and growth, changes in the colour and shape of roots, the nature and number of lenticels and cracks on the roots caused by excess of moisture and lack of oxygen in the soil. A researcher excavating roots should be familiar with the characteristics of the above-ground system, i.e. he should know the dimensions of the fruit tree studied and the properties of the soils of the whole plantation. Furthermore, samples of soil should be taken from under the tree at different depths, namely, at the depth of the upper roots (3 to 10 cm), at the depth of the bulk of the horizontal roots (15 to 60 cm), at the lower border of the roots (60 to 120 cm), and then at intervals of 50 to 100 cm down to the depth of vertical root penetration. Each soil sample must bear a label showing the soil and subsoil genetic horizons.

Simplified Modification of the Skeleton Method

Depending on the purpose of studies only the horizontal roots need be exposed sometimes. Thus, Solyanikov (1927) carried out a very careful excavation of all horizontal roots of an apple tree in the Moscow Region to obtain a detailed picture of root distribution.

Excavation of the whole root system or even of only the horizontal roots, though yielding valuable results, is a difficult procedure, which is the principal drawback of this method. Excavation of the root system of fruit trees, especially those 8 to 10 years of age and older, and showing it on a plan is a very time- and labour-consuming task which is also tedious and expensive. For instance, it took a skilled assistant six weeks to excavate the whole root system of a 12-year-old Kandil Synap apple tree (grafted on wild apple *M. Sylvestris*) when we used the skeleton method for the first time in 1925 in a Crimean orchard. A root system 11 m in diameter and 4 m in depth was excavated and a plan drawn, for which purpose at least 100 cu m of soil was removed.

Budagovsky (1953) also claimed that excavation of the whole root system was very difficult and expensive. To unearth the root system of a 14-year-old Pippin Shafranny apple tree growing in Michurinsk about 95 cu m of soil was removed, and what is more all the roots were carefully freed from earth.

In experiments conducted by Breviglieri (1953) in Italy three men unearthed the whole root system of an apple tree in two to three weeks, removing 40 to 60 cu m of earth, while two assistants recorded and drew the roots on a plan.

That is why many researchers excavated only a portion of the root system, which was justified by the fact that in most cases the uncovering of a half or even a lesser part of it yielded sufficient information to gain a clear idea of its depth and the nature of its distribution in the soil. The root system is apparently also characterized by parallelism, i.e. similarity in the architectonics of its separate parts, a phenomenon established by Schitt with respect to the above-ground parts of fruit plants. The existence of such parallelism may justify the excavation of only a part of the root system.

We examined two adjacent 30-year-old apple trees of

the same variety grown on the same rootstocks in the Crimea under similar soil conditions and management, and excavation of one-fourth of the root system of each tree produced strikingly similar results as to the depth of rooting and the location of horizontal and vertical roots. The excavation of the whole root system of a 12-year-old apple tree from the alluvial soil in the Crimea yielded very interesting and important findings: one half of the root system extended to a depth of 2 m, while the other half penetrated to a depth of 4 m. This can be attributed to the fact that long before the tree was planted the river current had formed a deposit of compacted gravel at a depth of 2 m. It is obvious from this that when only a portion of the root system is excavated the soil conditions must be considered, particularly in the case of soils of alluvial and deluvial origin.

Some researchers believe that it is sufficient to unearth only one-sixth (Dragavtsev, 1938) and even one-eighth (Galushka, 1956) of the root system.

When we unearth only a half, and especially only one-quarter, of the root system we usually raise the thicker roots and fasten them to skeletal branches of the stem (after they are recorded on the plan) to facilitate the further excavation of other horizontal roots and then of all the vertical roots. When the excavation and drawing of the roots was completed we replaced the horizontal roots at the original depths, covered them with earth, and watered them. With the technique described this one-fourth of the root system remained intact. The tree recovered and continued cropping.

We partially used the skeleton method to determine the depth of soil treatment and fertilizing. The roots of an apple tree in the Crimea were unearthed in a quadrant or an octant to depths of 10, 15, 20, and 25 cm to establish the amount and thickness of the roots that would be injured when the soil was ploughed to the respective depths. All the roots obtained were divided only into two groups, up to 0.8 cm thick and thicker than 0.8 cm, and their total length was recorded. Then we recorded the number of roots of either thickness found at different distances from the trunk (1, 2, 3, 4, and 5 m) and at different depths (10, 15 cm, and so on).

We adopted the thickness of 0.8 cm (that of a pencil) as a criterion long ago because our experience of many

years had shown that roots of thickness 0.8-1.0 cm and more regenerate poorly, especially in arid and non-irrigated areas. Hence, roots thicker than 0.8-1.0 cm should be protected from injury during ploughing.

By means of comparatively rapid shallow excavation it is possible to find out the location of thin roots, particularly the absorbing ones, which extend in the direction of the branch-spread periphery and beyond it in the first half of the tree life and start to spread anew from the trunk to the periphery in the second half owing to a new growth of roots from the root collars (rootstock). This modification of the skeleton method enables the fruit grower to discover quickly accumulations of absorbing roots at any age of the tree and supply these sites with moisture (irrigation) and nutrients (fertilizers). Excavation of roots lying in the surface layer of the soil can also be done for diagnosing certain adverse phenomena occurring in fruit plants in order to eliminate them effectively and in good time.

Treatment of Data Obtained

The results of studies are usually presented in the form of one or two plans of horizontal and vertical roots, mainly skeletal and semiskeletal, and retained portions of fibrous roots. In addition, a journal is kept in which all important features are entered (changes in root colour, occurrence of worm burrows, etc.), photographs are taken, and, if necessary, collections of roots and soil samples are made.

After the whole root system (or a part of it) is excavated, the main task consists in making accurate drawings of its horizontal and vertical projections separately. The horizontal roots are represented by lines of proportional thickness (to a scale of 1:10 or 1:20), therefore the numerator of the fraction (root thickness, mm) can be omitted. The denominator (depth, cm) is usually left on the plan. The slower and more carefully the root system is excavated the more thin roots are recorded.

Prior to recording the vertical roots on a new plan, all the horizontal roots are drawn, taking into account their thickness and depth, but no fractions are given. Then the vertical roots are drawn in accordance with the numbers in the small circles and the points of their branching from the horizontal roots (Fig. 31).

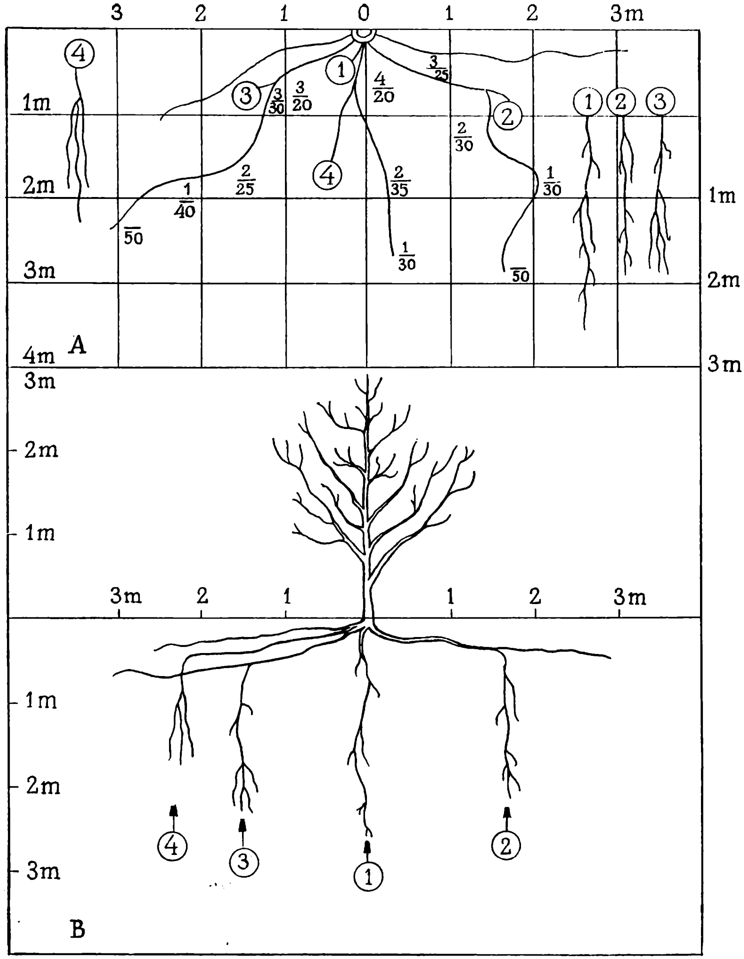


Fig. 31. Root plans:
A—**first representation of horizontal** and vertical roots; *B*—plan **of vertical** roots

In drawing vertical roots care should be taken to show their actual distances from the trunk. For instance, when projected in the vertical direction, root No. 4 shown in Fig. 31 will be found directly under the trunk, whereas it is actually about 2 m away from the trunk.

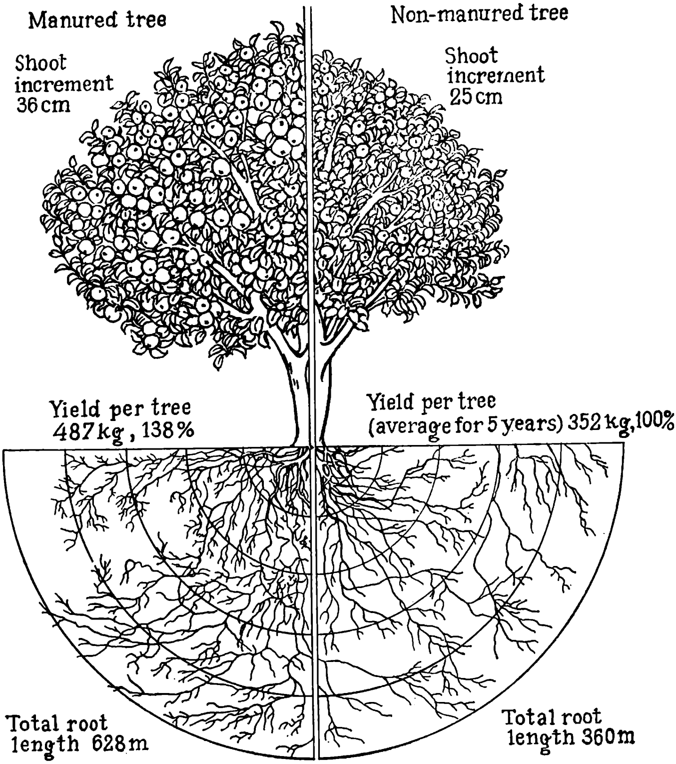


Fig. 32. The effect of systematic application of fertilizers on the development of Golden Winter Parmen apple tree (after Priymak, the Kuban area)

After establishing the true picture of vertical root distribution we were able to reveal a very important fact: in Crimean orchards with hole irrigation the roots found directly under the trunk did not penetrate downwards, but first extended sideways and then entered the deeper layers of the soil. This was due to an overmoistened layer of soil (dead cylinder) up to 1-1.5 m in diameter formed under the trunk as a result of systematic hole irrigation.

The results obtained by using the skeleton method, or more precisely, by excavation of the root system in studying and comparing two alternative experiments with fertilizers were represented by Priymak (1957) in a very inte-

resting form—as horizontal profiles and adjacent sketches (see Fig. 32). Belski (1966) drew plans of four excavated root systems (each from a quadrant) of different varieties of sour cherry grown on similar rootstocks (Fig. 33). Figure 34 illustrates a diagrammatic representation of the root system of a berry plant.

Schitt *et al.* (1936) conventionally regarded the root-system branchings of the two last orders as thin roots. In tabulating the data and in drawing diagrams the total length of skeletal roots or the amount of fine roots recorded during excavation was taken as 100 per cent; a record was made of roots in each concentric layer of the soil 0 to 1 or 1.4 m thick of radius 1, 2, 3, etc. metres (in horizontal zones); the percentage of different kinds of roots was also estimated.

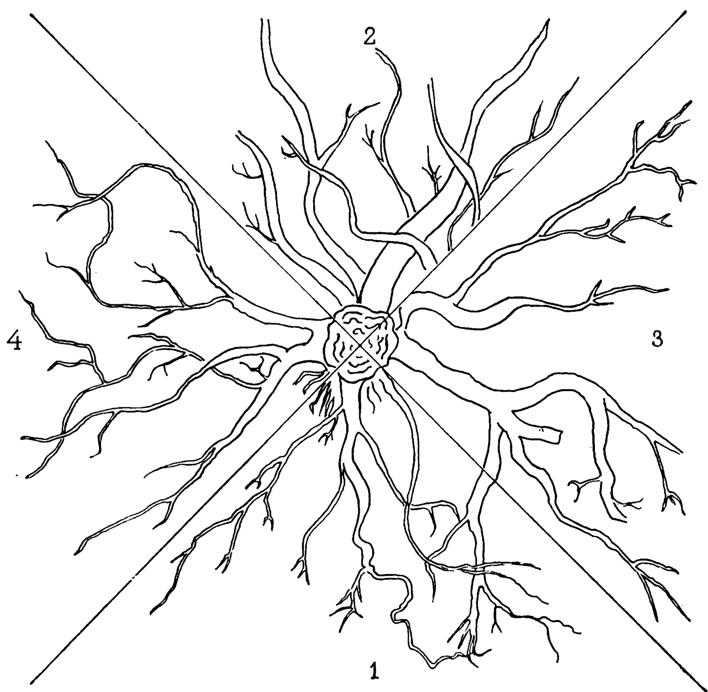


Fig. 33. Horizontal distribution of the root systems in cherry of the Monomakh Korotkonozhka, Angliiskaya Rannyaya, and Shpanka Krasnokutskaya varieties (after Belski)

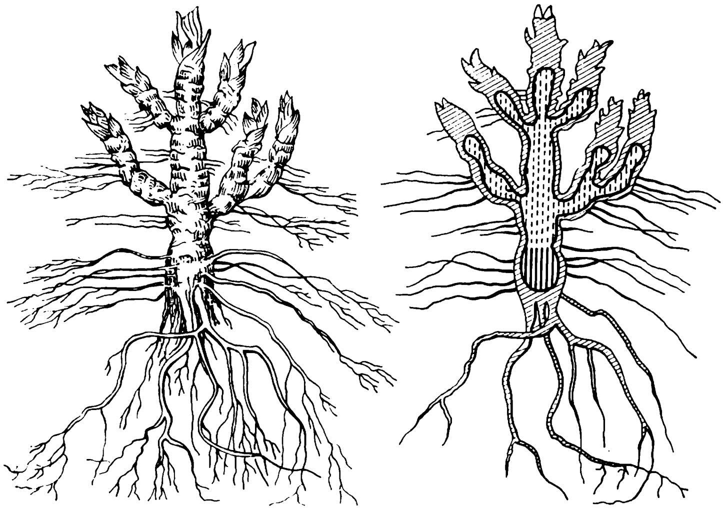


Fig. 34. Four-year-old strawberry plant, general view (left) and longitudinal section (right) (after Reznichenko)

Evaluation of the Method and Examples of Its Application

The skeleton method provides a pictorial representation of the whole root system or of its portion. Excavation and drawing of the first plan and then the final one to a chosen scale give a clear idea of the distribution of the root system in the soil and subsoil and of the ratio of its dimensions to those of the above-ground part of fruit plants. Drawings of the horizontal and vertical profiles of the root system show the location, stand-thickness, and depth of the bulk of the horizontal and vertical roots, the absorbing roots included, and their relation to the soil horizons. This method is suitable for studying the root system of fruit plants, berry plants, and other tree species whose roots are more resistant to breaking than the roots of herbaceous plants.

Numerous researches carried out by scientists in many countries (the USSR, USA, England, Japan and other countries) with the use of the skeleton method enabled them to reveal the structure and distribution of the root system of the main fruit plants in commercial zones of fruit growing and thus to specify a number of soil treatment measures and methods applied in orchards and berry plantations.

With the skeleton method we were able to confirm that fruit plants also have bands consisting of 10 to 30 roots and even more and extending to large depths of 3 to 5 m along the passages of rainworms. We also revealed two-layer distribution of the root system, a distinct "claw" shape of the roots where they pass beyond the irrigation hole under the tree, free interlacing of roots of one and the same or of different species and the opposite phenomenon of their drawing away from one another, accretion of roots on meeting, a change in the root colour caused by excessive soil moisture, etc.

As was mentioned above, on the first plan the denominator of the fractions at all distinct bends of each root indicated the root depth throughout its whole length. In our earlier researches there were hundreds of such figures on each plan. It is advisable to join them into several groups so that the nature of the distribution of the main mass of horizontal roots is evident. This will also help in rational selection of many measures of soil management, such as the depth of ploughing, depth of irrigation trenches, depth of fertilizing, and so on.

A carefully excavated and accurately represented root system helps to determine the amount and length of the roots (a) inside the irrigation hole, within the horizontal projection of the branch spread and beyond it (Table 15), and (b) in different soil horizons. Therefore, the total length and amount of roots, and the depth of rooting can also be estimated.

Table 15

Amount and Length of Apple Tree Roots

Characteristics	Horizontal roots			Vertical roots	Total
	Total	within branch-spread boundary	beyond branch-spread boundary		
Number of roots	3,528	1,088	2,440	2,676	6,204
%	57.0			43.0	100.0
Length, m	611	223	388	524	1,135
%	51.6			48.4	100.0
Depth, m	—	—	—	3.7	—

CHAPTER 4

THE MONOLITH METHOD

Specific Features and Purpose

The monolith method consists in dry excavation of the whole root system of a plant or only a part of it by gradually driving a trench and removing small soil monoliths (blocks) to determine the weight, amount and length of the roots contained in each monolith. The method gives full information not only on skeletal and semiskeletal but also on small roots (absorbing roots included), and on the depth of rooting with reference to different horizons of the soil and subsoil.

The monolith method, like the skeleton method, has been used for a long time. It was first employed to study the root systems of grasses, and later those of trees, including fruit plants. It was first proposed in France by Müntz and Jirard (1891). They drove a trench around a tree, isolated a column of soil containing the root system and divided it into 25-cm layers. Then they removed each layer of soil in succession, washing out and weighing the roots each time. The American scientist King (1893) separated the roots by washing them out of a soil column screened off with a metal gauze case. Later on, the Russian scientists Rotmistrov (1907), Sokolovsky (1913), and Modestov (1916), and the American scientist Weaver (1919) improved and modified this method, using it in studies of herbaceous plants.

As far back as 1916 Vorobyev suggested determining not the amount of roots but their "functioning surface", i.e. the most extensively branching zone of the absorbing roots. In the USSR, one of the first to use the monolith method on a wide scale was Kachinsky (1925). He modified the technique suggested by Müntz and Jirard, introducing the following basic amendments: (1) preparation of monoliths with a root system of herbaceous plants; (2) dividing the monolith into

portions according to the genetic horizons (whereas Müntz and Jirard divided the soil into equal layers of 25 cm); (3) washing the roots on sieves and freeing them from soil and foreign matter; (4) recording the roots according to weight, length and functions: active (absorbing) and inactive (conducting) roots.

Kachinsky's method has a number of advantages; it provides a sufficiently objective quantitative picture of the root system.

The British scientists Rogers and Vyvyan (1934) were the first to develop and apply on a wide scale a similar method for studying the root system of fruit trees. They called it the *block method.* In fact it is essentially the familiar monolith method and will be referred to as such.

The monolith method is preferably used in two kinds of research: (1) a more detailed study of the root system, differentiating the roots by thickness, length, amount, depth of penetration and distribution according to the soil horizons; (2) simple investigations, such as recording roots in the upper horizons (the bulk of horizontal roots, particularly absorbing roots), studying the effect of various soil treatments on the growth and development of the root system and the effect of fertilizers and irrigation so as to take urgent remedial measures and modify the agricultural techniques.

The monolith method makes it possible

(1) to record all, without exception, roots of the root system, including absorbing (at the time of excavation) roots, to get a comprehensive picture of root distribution in different soil horizons, and to determine the character of horizontal root spread from the trunk to the periphery of the branch spread and beyond it;

(2) to find the quantitative and qualitative relation between the skeletal (thick) and thin roots (absorbing roots included) for different horizons and depths, which can be done by detailed division of all roots into several groups according to thickness;

(3) to reveal the peculiarities of the growth and development of the root system of a plant depending on the species, variety, rootstock, age of plant, soil conditions and treatment;

(4) to obtain more detailed information on the vertical distribution of the roots near to the surface;

(5) to excavate only part of the root system; this will yield sufficiently reliable results in studies of many problems.

The monolith method is undoubtedly of great value in solving many theoretical and practical problems of fruit growing. Having obtained the necessary information on the distribution of the root system from a detailed study of the whole system or a part of it, the fruit grower can decide on the cultural measures and techniques needed, such as the depth of ploughing and loosening, zones of fertilizing and irrigation in the nursery, orchard, and berry plantations.

Techniques of Excavation and Preparation of Roots for Grading

Rogers and Vyvyan (1934) thorougly elaborated the monolith ("block") method and employed it widely in studies of the root system of fruit trees. The initial purpose of their investigation was to examine the development of the root system of identical stocks in soils treated in different ways. The roots were excavated by the skeleton and block methods simultaneously. The objects of studies were fruit-bearing apple trees. The techniques of excavation and grading of roots were as follows.

The surface of the soil presumably containing the entire root system of the tree was divided into equal squares. The soil was removed in blocks of 50 cu cm from all depths except for the top block, which was divided horizontally into three equal layers of about 17 cm each for better estimation of the vertical distribution of the fibrous roots, which are especially abundant in the top layer. The arrangement of the root monoliths intended for excavation is shown in Fig. 35.

The removed blocks of soil were immediately placed in labelled bags, and then in airtight tins, and taken to the laboratory, where the roots from each tin were carefully washed, grouped according to length and thickness, and weighed to within 0.1 of a gramme. Preliminary tests showed that the best results were obtained if the interval between washing and weighing was not longer than one hour. After washing much water still clung to the root surface and would have affected the weight data if weighed immediately. But when the roots were held exposed for more than

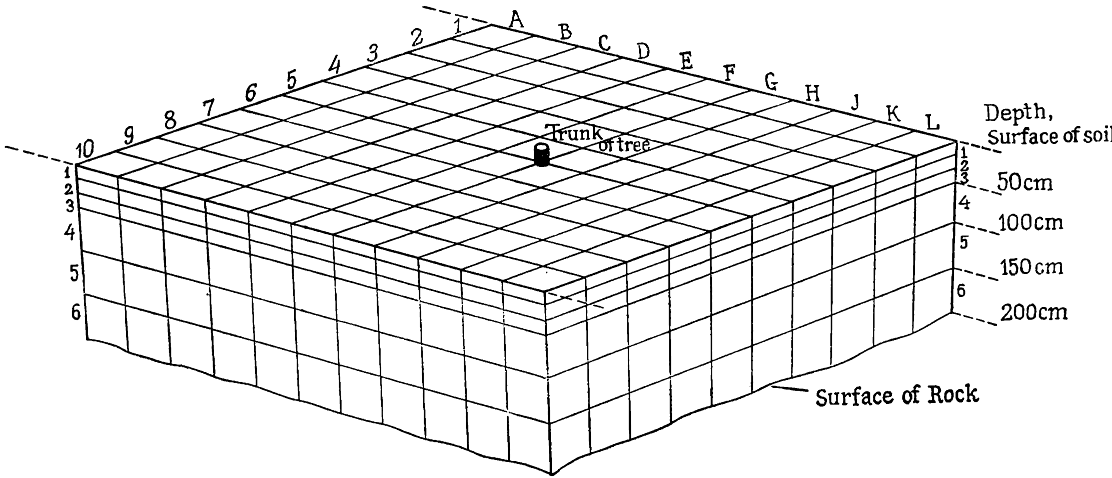


Fig. 35. Arrangement of monoliths (blocks) in block method of excavation (after Rogers and Vyvyan, England)

one hour they partly dried off, the smaller roots even drying completely and, consequently, losing relatively more weight than the larger ones. It might seem that errors could have been avoided if dry weights were used instead of fresh ones, but this proved less convenient and impracticable since for comparative purposes one would have to obtain the dry weight of the aerial portions of the tree, the branches and fruits in particular, a task extremely labour- and time-consuming.

So, though the advantages of determining the dry weight were obvious, the authors found it more convenient to compare the fresh weights. They did not let the roots dry and weighed them within one hour after washing, and also obtained the fresh weight of the prunings and fruit.

According to Rogers and Vyvyan, 600 bags with roots (each from one small block of soil) were sometimes obtained on excavation of the root system of a single tree, and after grouping up into grades their number increased to several thousands. Considerable time was also needed for determining the weight of the branches and fruit.

The method described permits determining the actual fresh weight of each grade of roots in each separate block of soil.

Root thickness was measured with the aid of a board with a row of eight pegs driven into it at intervals of 1, 2, 4, 8, 16, 32, and 54 mm. All the roots were grouped into seven grades, according to the space through which they could pass. Roots 1 mm thick were classified as Grade I, those that passed through the 2-mm space were referred to Grade II. Grade III included roots 2 to 4 mm thick, Grade IV between 4 and 8 mm, Grade V between 8 and 16 mm, Grade VI between 16 and 32 mm, and Grade VII between 32 and 64 mm. No roots thicker than 64 mm were found. If the ends of a root differed in thickness, it was cut in two, and the parts were referred to the respective grades.

According to Rogers *et al.*, up to 60 tons of soil had to be moved to excavate a single apple tree on dwarf rootstock, and a total of over 100 root systems were completely excavated.

The monolith method enables one to obtain extremely detailed and reliable data concerning the horizontal spread of a root system in the soil and its distribution from the trunk outwards to the periphery of the branch spread and beyond it.

Simplified Modification of the Monolith Method

Rogers and Vyvyan found examination of the whole root system a cumbersome task, and resorted to excavating only part of it. At first they used a "combined" method, combining the skeleton method with some of the advantages of the block method, namely: the trench was 50 cm long, as before, but the roots were obtained at the boundaries of every one-metre square, and only from two depths, above and below 30 cm. Later they cut roots at the boundary of each 50-cm square, from four depths—0 to 30 cm, 30 to 50 cm, 50 to 100 cm, and below 100 cm. The roots were washed and weighed on the spot. They found that the proportions of the thicker roots varied greatly within one and the same stock. Sometimes they divided the roots only into three thickness grades: less than 1 mm, 1 to 5 mm, and more than 5 mm. In short, Rogers and Vyvyan studied only part of the root system and reduced the number of thickness grades, taking into account only the weight, number, and length of the roots (when dry), and no longer determined the fresh weight of the roots.

In the USSR the monolith method was widely employed by Schitt and his colleagues (1936) during field surveys of vast territories in several regions for determining whether their soil was fit for fruit growing. Using a simplified monolith technique they chose the best soils for future orchards and, in addition, made some conclusions which proved valuable in practice and fully justified the adopted method of excavation of the root system and the grading of roots according to their length and number.

As suggested by Schitt, one-fourth of the apple tree root system was usually taken, the soil being removed in 20-cm layers, in the form of circular arcs or bands, from one-quarter of the circle at distances of 1, 2, 3, 4, etc. metres from the trunk and to the end of the roots. The soil was cut in monoliths in segments 25 or 50 cm wide, depending on the purpose of the investigation and the size of the tree. The genetic horizons were taken into account wherever possible (in many cases the borders of the soil horizons were obscure).

The roots freed from the soil were gathered, washed, and grouped according to thickness into the following grades: thicker than 10 mm, 10 to 5 mm, 5 to 2 mm, and less

than 2 mm. The number of grades distinguished depended on the size of the trees and the purpose of the studies. After the roots had been graded their length was measured and they were weighed. Special attention was paid to the group of fibrous roots less than 1 mm thick, particularly to their distribution in depth and in the direction from the trunk to the ends of the skeletal roots. It was found, for instance, that a Parmen Zimni Zolotoi apple tree in the Kuban area (on wild apple rootstock) had 69,320 fibrous roots per cubic metre. Using the root coefficient established by us, this will account for 242.6 m of fibrous roots per one cubic metre for the roots of a grown-up apple tree.

Rybakov (1935) excavated the root system of a twenty-year-old Antonovka apple tree (on wild apple rootstock) growing on deep and degraded chernozem in the area of Michurinsk in the Tambov Region. He cut layers of prism-shaped soil monoliths with a 20×10×10-cm base, beginning with the top layer, without employing boxes. Then he sorted the roots into thickness grades of diameter 1 mm, 1 to 3, 3 to 5, 5 to 10 mm, and more than 10 mm, and determined their dry weight in grammes per 10 kg of absolutely dry soil.

Kalmykova (1938) used the monolith method for studying the distribution of conducting and absorbing roots in the soil and subsoil of the Alma valley in the Crimea in relation to the method of orchard irrigation. In her opinion, the monoliths cut by Rybakov were too small, and she suggested that 1) their size be increased to 50×20×10 cm, and 2) the monolith be cut from three concentric circles (bands), no less than eight to ten samples from each circle.

Dragavtsev (1938) cut 100×20×10-cm monoliths along 60° arcs plotted at a distance of between 1 and 2 m from the trunk for a young tree (under ten years of age) and between 2 and 3 or 3 and 4 m for a mature tree. Excavation was done along the genetic soil horizons. Each monolith was placed in a specially constructed wire cage pierced with wire prongs for correct fixation of the roots, and the roots were carefully washed free of the soil by means of a pulverizer of a garden sprayer connected to a water tap by a hose. The selected roots were tied in bundles separately for each metre of a segment of each genetic horizon, then labelled, and temporarily covered with earth. Dragavtsev preferred to excavate segments on the north-eastern side of the tree,

since preliminary studies showed that side to be most typical.

Chefranov (1939) used the monolith method for studying the influence of ground waters, and even bogs, on the growth and development of the apple tree root system in river valleys of the Crimea, recording only the number of roots. He believed that the greater number of experimental replications had enabled him to solve his problems successfully and to give some valuable recommendations on agricultural technology of fruit species.

Batjer and Sudds (1937) dug a trench 60 cm long, 30 cm wide, and 30 cm deep on each side of an apple tree, 1.8 m away from the trunk. They cut the soil in 16-cm layers, freed from the soil all roots thinner than 10 mm, grouped them into two thickness grades, and dried them at 100°C.

Schmidt and Nutman (1940) maintained that the monolith (block) method could be employed in studies of the root system of fruit trees growing in East Africa, with intact soil monoliths of any conceivable size. The limitations in such cases will evidently consist in transportation difficulties or stony soil. They used the method successfully for examination of coffee tree roots with a soil mass weighing about two tons; the soil was porous and light, containing only a negligible proportion of stones.

Vinograd (1941) investigated the root system of four-year-old apricot trees by excavating only an octant from the soil around the trunk along the whole length and depth of root spread. The roots contained in the monoliths were washed and graded, the absorbing roots being recorded separately. The percentages (by length) of the absorbing roots and of the total root length in each segment were estimated.

Shumakov (1949) considered that for quantitative estimation of the roots of a thirty-five-year-old oak at different horizons it was quite sufficient to recover them from one square metre of the surface area under the branch spread.

The monolith method was employed by Kabluchko (1955) in studies of the root systems of many fruit species in Moldavia in the period between 1948 and 1950. To determine the distribution of the roots in depth and along the circumference of the branch spread he first dug, starting from the trunk, a band 1.5 to 2 m deep and just as wide, and thus the main bulk of these roots was recorded. Then he chose a site with an average number of roots of average thickness,

marked a trench 75 cm wide, and drove it in 20-cm layers from the periphery of the branch spread towards the trunk, assuming it to be the centre of the circle. The length of the trench was half the inter-row space, its depth reaching 2 to 2.5 m.

Sometimes the trench was worked along a large main root. The roots were unearthed and recorded in 20-cm layers and 1-m zones. One or two hours after they had been washed free from soil and dried in the air, all the roots were weighed, their length measured, and then they were graded according to thickness. Grade I mainly contained roots ranging in thickness between 0.2 and 2 mm, including fibrous ones. The authors found, however, that not all the fibrous roots were recorded because they had been broken off and lost with the soil. The other grades included roots thicker than 2 mm.

The authors believed that though the method was not faultless it gave sufficient information about the zone of distribution of absorbing roots and the depth of their spread for individual species and varieties of fruit plants.

After washing the roots of tree species Krasilnikov (1950) grouped them into five thickness grades: less than 1 mm, from 2 to 5 mm, from 6 to 10 mm, from 11 to 50 mm, and more than 5 cm. Then the amount of each grade was estimated, the roots dried, and weighed.

Budagovsky (1953) suggested a less laborious excavation method, which he tested himself. He dug trenches one metre wide (Fig. 36) and drove each trench in one-metre squares from the periphery to the trunk, where it ended in the shape of a triangle (0.5 square metre); this was convenient for further calculations. The roots were removed along the

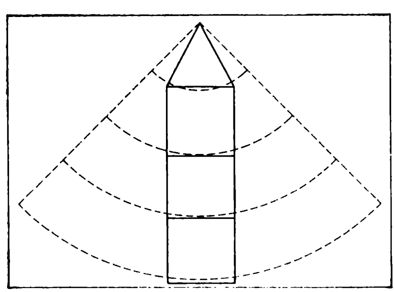


Fig. 36. Excavation of the root system:
thick lines indicate the projection of trench excavation; dotted line indicates the projection of sector excavation (after Budagovsky)

genetic soil horizons separately from each one-metre square. The method involved less work.

Budagovsky suggests that in excavations for studying absorbing roots monoliths be cut for washing, which, together with the first method, will yield more complete information on the life of the root system.

Zhilitsky (1953) found that with an increase in the distance from the trunk the volume of the soil occupied by the roots increased considerably. According to his findings, the length of roots per one square metre of soil was 227.9 m in the soil immediatedly adjoining the trunk, 151.2 m at a distance of 1 to 2 m from the trunk, 147.2 m at 2 to 3 m, and 74.4 m at 3 to 4 m. The ratio of the soil volumes in these zones was 1:3:5:7, respectively, whereas the variations in the stand thickness of roots were in smaller proportions. This clearly showed that the peripheral zones, being richer in roots than the zones closest to the trunk, are important for the tree.

The Japanese researcher Yasuda (1954) recommended the use of a frame in studying the root system of fruit plants. A vertical layer of soil is collected by means of a frame, placed on boards, and the roots are carefully washed free from the earth. A frame 45 cm long and 60 cm wide grasps a 2.5- to 3-cm layer of soil.

Rubin (1953) found it more convenient to collect the monolith in a $43\times35\times40$-cm box with a sieve-like bottom, which allows the roots to be washed right in the box.

Of great methodical value is the work carried out by Garyugin (1955) in the Rostov Region for estimating the number of vertical roots of fruit species (apricot, cherry plum, sour cherry, walnut, plum, mulberry, apple); the rootstocks for some of them were seedlings of identical species. One or several trenches 3 m long, 1 m wide, and 4 m deep were dug for each tree. The distribution of the root system to a depth of one metre was studied in 20-cm layers by the monolith method. At depths exceeding one metre only the exits of vertical roots at the bottom of the trench (as they were excavated) were recorded at every 0.5 m. With this technique of obtaining samples and washing the losses were negligible. Experience proved the efficiency of the method. Sibukova (1953) suggested employing a larger frame than that used by Yasuda, namely, one up to 90 cm long and up to 50 cm wide which allowed the thickness of the

root-containing soil layer to be increased to 10 cm. The trench wall nearest to the trunk was evened out with a knife, then freed from soil with an awl to a depth of 5 to 10 mm so that the root tips could be seen better, after which the frame was set against it so as to facilitate recording of the number, location, and thickness of the roots. Some roots passing near to the walls of the trench were also exposed. Roots were excavated from under two trees of each species. Most were of small diameter.

Ivanova (1957) examined the root system of gooseberry by the monolith method. She cut layers of soil less than 10 cm and 10 to 20 cm, and washed the roots free of earth.

Vashchenko (1966) studied successfully the root system of apple trees growing on the sand shores of the Don. He constructed a root cutting device which could be driven into the soil not vertically, but from the side of the trench wall, perpendicular to its surface, thus preventing the collapse of the trench. The device (Fig. 37) is a rectangular box with 2-mm steel walls. The two side and one bottom edges are well sharpened for cutting the roots. For greater strength cross bars are welded on the opposite side and by

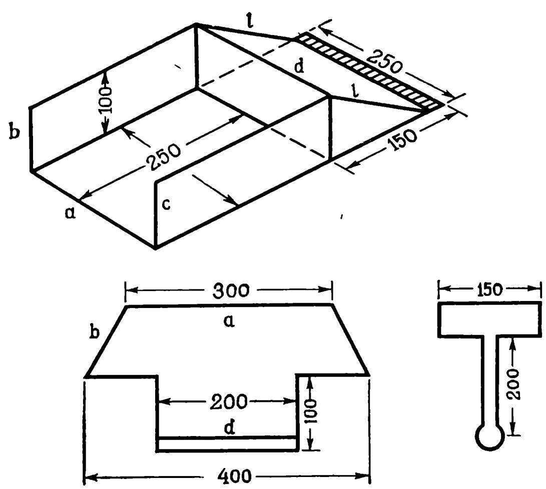


Fig. 37. Root-cutting device for removing monoliths measuring 250×250×100 mm; *a*, *b*, and *c* are cutting edges; 10-mm steel bars are welded to the sides for greater strength; a wooden mallet is shown on the right. All measurements are given in mm (after Vashchenko)

hitting them with a hammer (or the head of an axe) the root cutter is driven into the soil. The monolith is cut with a trapeziform steel knife slightly wider than the root-cutter. To remove the monolith the sharpened sides of the device are placed against the vertical wall of the trench and then driven into the soil. After this the knife is placed vertically at the ends of the device and driven into the soil with a light stroke of a mallet, thus separating the device with the monolith from the soil. If the cut surface proves to be larger in length than the root-cutter, it is trimmed with the same knife, but a vertically driven knife usually moves directly along the root-cutter edges so that the cut does not have to be corrected.

The monoliths obtained were water-washed free of soil on wire sieves that had round openings 3, 2, 1, and 0.5 mm in diameter. The sieves were fitted into rectangular wooden boxes 5 to 6 cm high. To make the sieves steadier three wooden bars were fastened to the bottom of each box and a net placed on them. The boxes with the sieves were put one on top of the other so that the sieve with 3-mm openings was at the very top, that with 2-mm openings underneath it, followed by the sieve with 1-mm openings, and finally by the one with 0.25-mm openings. The boxes were fastened together with iron hooks, and a netted lid (1-mm mesh) with a handle was fitted over them. The set of four sieves was 35 cm high, 65 cm long, and 34 cm wide.

To wash the roots free of soil the monolith was placed either whole or in parts on the top sieve and covered with the netted lid. Then the whole set was submerged in a water container or in a reservoir and set in motion by hand, so that the soil separated from the roots. When needed the top lid was removed and the clumps of soil were carefully divided by hand. The roots can also be washed with a stream of water from a water pipe or a hose.

Washing can also be done using only one sieve with 1-mm openings. The roots were removed from the porous layers of soil in monoliths and the soil was sifted through the sieve. After this the roots were picked out, carefully washed with water, and grouped into four grades according to the diameter: (1) less than 1 mm, (2) 1 to 3 mm, (3) 3 to 10 mm, and (4) more than 10 mm.

The living and the dead roots of the plants and the organic remnants were recorded separately. The root volume

was determined in a special measuring glass, and the root length and average diameter were measured. Each grade of roots was placed into a weighing bottle (which is very convenient), dried first to air-dry weight and then dried in a thermostat to absolutely dry weight, after which it was weighed.

The monolith method was employed at the Pomology Department of the Timiryazev Academy (Kulenkamp, 1966) with the following modifications. One-eighth of the root system of an apple tree was excavated in monoliths 25 cm high, 50 cm wide, and one-eighth of the circumference in length (as the trench approached the trunk the length of the monolith decreased). The first monoliths were removed from the middle of the inter-row space 3.5 to 4 m from the trunk. The number of roots exposed on the trench wall was determined and a soil-root record drawn up showing the soil horizons or layers and the root sizes. Monoliths were excavated at distances of 4 to 4.5 m or more from the trunk only if they contained roots of the apple tree under study. Roots from each monolith were collected separately into polyethylene bags, washed free of soil, dried for two hours, and then weighed. The monoliths were excavated one after another from the middle of the inter-row space towards the trunk.

Owing to the monolith method it was possible to determine the root weight for a distance of up to 4 m from the trunk, layer by layer, to the ultimate depth of vertical root extension. The amount and length of roots were recorded for five grades in each monolith and for the whole octant of the root system of the tree. Roots thicker than 10 mm and thinner than 1 mm were weighed separately. The root length was measured by grades: for roots with a diameter of more than 10 mm, 5 to 10 mm, 3 to 5 mm, 1 to 3 mm, and finally, less than 1 mm. The latter was determined by measuring the length of 1 g of roots and then multiplying the result by their weight in the sample. All the roots were weighed again after having been air-dried. This method allows one to determine most accurately the amount of roots in the different horizons and layers of the soil and subsoil, the horizontal-to-vertical root ratio in them, and the length and weight of these roots.

Rakhteyenko and Yakushev (1968) suggested that for studying the root systems in forest stands a trial area not

smaller than 500 sq m should be chosen first. Then the height and diameter of the trees in this area must be measured, the distribution of the trunks marked on a plan, and the herbaceous covering described. Using the measurements and the plan the site of the trench is chosen between average model trees.

These studies showed that in order to obtain quantitative characteristics of the actual distribution of the roots of forest plants in the soil, records must be made of their entire spread. For this purpose the trenches in the spaces between the rows must be dug so that their width is the same as the width of the spaces, while their length extends over an area covering not less than two neighbouring trees in the row.

The plan of a trench driven in forest cultures is shown in Fig. 38. Sites for digging trenches in natural plantations are chosen on the same principle. At least three trenches are driven across each trial plot (Rakhteyenko, 1963).

To determine the ratio of the above-ground (stem) to the underground parts of the plant, the weight of the former is determined, for which the model trees growing on the border of the trench are cut down and divided into parts: trunks, branches, and leaves (or needles).

The roots are unearthed in the trench in layers of 10 to 20 cm down to their termination, and to separate them the soil is sifted through a sieve with 2 to 3-mm openings. The washed roots are first grouped according to species and then

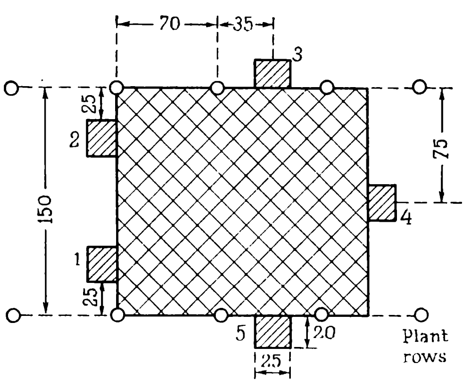


Fig. 38. Distribution of sampling quadrants (1-5) in forest stands (circles indicate tree trunks) (after Rakhteyenko and Yakushev)

into three thickness grades: roots below 1 mm are referred to the first grade, 1 to 3 mm to the second, and 3 mm and more to the third grade. Roots of the second and third grades are classified as large, those of the first grade, as thin (small).

When the roots are sorted, those of herbaceous plants, dead roots, and organic remnants in which no definite parts of the plants can be distinguished are recorded separately. Then the roots and above-ground parts of the plants are dried and weighed. After that the amount of dry roots per sq m is calculated from the formula $x=\frac{P_1}{S_1}$, where P_1 is the weight of roots from the trench area and S_1 is the trench area, sq m. The amount of roots per one model tree is estimated from the formula $x=\frac{P_1S_2}{S_1N}$, where S_2 is the size of the trial area (sq m), and N is the number of trunks on it.

After the trench has been sunk a plan of the root system is drawn. This is done by carefully uncovering the roots on the trench wall to a depth of 10 to 15 cm and marking their position on graph paper with the aid of a scale grid. The horizontal spread of the root system of a tree is determined by the method of dry excavation, removing the soil from one-fourth of the area occupied by the root system.

The method of dry excavation of the roots on the trench walls and from the surface of the soil is an important supplement to the method of quantitative recording.

From one of the trench walls a plan of the soil profile is drawn, the density of soil horizons determined, and samples of soil are collected for bulk, agrochemical, and mechanical analyses and for testing its physical properties.

When only the stand-thickness of the *thin* roots of tree species or of the roots of herbaceous plants was studied, Rakhteyenko and Yakushev used small monoliths 20×25 cm in size. The monoliths were collected in five replications from typical sites of the trial area (Fig. 38) to the depth of penetration of the main root mass. The authors (Rakhteyenko, 1963) constructed a special device, a root-cutter (Fig. 39), for removing soil monoliths with roots, which is now widely used by many researchers. The roots in the monoliths are washed free of soil in sieves with openings of 1 to 2 mm.

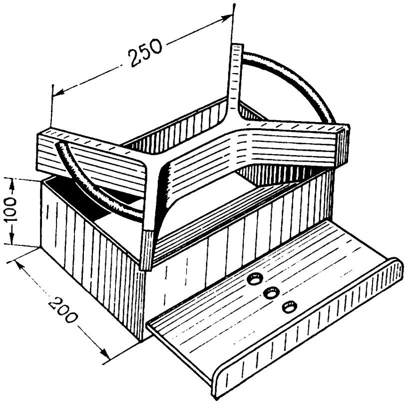


Fig. 39. Root cutter for removing soil monoliths with roots (after Rakhteyenko and Akhromenko). Dimensions are given in mm.

The method of root system examination elaborated by Rakhteyenko and Yakushev and tested in practice allows one to make a full record of both skeletal and thin roots occurring on a unit of plantation area.

According to Rustamov (1968), the technique for establishing the efficiency of the underground parts of desert communities is insufficiently worked out so far, though it is mentioned in the literature (Bazilevich and Rodin, 1956; Rustamov, 1965, 1967). Rustamov believed that of all the existing methods of quantitative recording of the underground portion of phytocoenoses the most suitable was the monolith method proposed by Kachinsky (1925) and later modified by Shalyt (1950, 1960). But removal of root samples from artificially limited areas by the monolith method will not meet the needs in studies carried out in semideserts and deserts because of the integrated nature of the vegetative covering. The combined efficiency of the root systems must be recorded; for this purpose Bazilevich and Rodin (1956) worked out techniques for recording the mass of roots over the entire area of plant nutrition that could be employed in desert communities.

Some details were added to the method by Rustamov (1965, 1967), who maintained that the area intended for the removal of samples of soil with roots (monoliths) in desert phytocoenoses should be a 0.25-metre square. With the sparse vegetative covering of deserts smaller areas are

of little use, particularly in determining the efficiency of the root system of shrubs and semishrubs.

It is best to cut the monoliths in 10-cm layers, and from top soil (not deeper than 20 cm) even in 5-cm layers. With this technique it is easier to detect the changes in the amount of roots with depth and to compare the layers. Simultaneously the soil profile is described and soil samples are drawn for analysis so that subsequently root distribution can be estimated in relation to the arrangement of the soil horizons.

Samples of soil with the roots (monoliths) are taken throughout the entire depth of root penetration in at least two replications. Though the bulk of roots of semishrub plants (wormwood, thistle, etc.) descend to a depth of 50 to 70 cm, samples should be cut from a depth of not less than 1 to 1.5 m. Samples from soil under ephemeras are usually collected down to a depth of one metre.

The choice and preparation of the experimental areas and the cutting of the samples are usually done by the method described by Shalyt (1960). The most efficient procedure for separating the roots from the soil is washing them with water. Dry treatment of samples with separation of the roots by hand, recommended by some investigators, is not reliable because the numerous thin roots contained in the soil cannot be recovered in this way.

During laboratory treatment root samples from each layer are weighed on an analytical balance, carefully sorted out and separated into root grades (according to the diameter), organic remnants (fragments of branches and fruits, seeds, etc.), and remnants of underground organs of stem origin (rhizomes, bulbs, etc.). Then the weight, volume, surface area, and length of every root grade are measured. Rustamov estimated the surface area of the roots from the formula for a cylinder wall: $S=\frac{4V}{d}$, where V is the volume of each grade, and d is the mean diameter. This method, suggested by Pogrebnyak (1927), was also used by Shalyt (1950, 1960).

Rustamov found, however, that calculations by this method were a tedious task requiring much time, especially if there were many grades. Besides, it involved the use of different units of measurement since the root diameters

were measured in microns or millimetres, the volume in cubic centimetres, and the surface area in square centimetres.

Since the studies involved a large number of samples the mathematical calculations had to be simplified. For this purpose special tables for estimating the surface area of roots of various diameters per 1 cu cm were compiled and used. From the formula for a cylinder wall given above Rustamov found that the surface area of roots with a diameter of 1 μ and a volume of 1 cu cm was 40,000 sq cm. Then he divided this figure by successively increasing diameters and found the surface area indices (factors) for the root fractions of respective diameters. As a result a table for calculating the surface area of roots with diameters of 1 to 1,000 μ and a volume of 1 cu cm was obtained.

A separate table was compiled for the grade of roots more than 1 mm thick. To determine the surface area of the root grade studied, the respective surface area factor is found in the table and multiplied by the volume of the given grade. For example, the average diameter of the root grade studied is 460 μ and its volume is 12 cu cm; we find from the table that roots of the given diameter with a volume of 1 cu cm have a surface area of 87 sq cm. Multiplying this figure by 12, we will find the surface area of the whole grade group. Thus the table greatly simplifies all calculations.

Rustamov found that the original method proposed by Kolosov for determining the total and absorbing areas of a root system by the methylene-blue method (see below) was not applicable under natural conditions. The method of calculation described by Rustamov is convenient primarily for estimating the total surface area of the root systems of phytocoenoses when the whole mass of roots in the given soil volume is determined. Besides, it readily yields the necessary initial information on the surface area of the root systems of plants and phytocoenoses that have not been studied yet in this respect. This refers particularly to desert plants and communities, whose underground portion has been insufficiently studied.

Rustamov determined the root length also with the aid of a specially compiled table. Shalyt (1960) suggested the use of formulas taking into account the surface area or volume of roots. Rustamov employed a formula taking

into account the root volume: $h=\frac{4V}{3.14 \cdot d^2}$, where h is the length (height), V the volume, and d the diameter of roots. First he found from the formula that the length of roots with a diameter of 1 μ and a volume of 1 cu cm was 1, 274 km. Then he divided this value by the squares of successively increasing diameters and found the root length factors in the respective grades. As a result, he obtained a table for calculating the length of roots with diameters of 1 to 1,000 μ and a volume of 1 cu cm. A second table for estimating the root length of grades with a diameter of more than 1 mm was compiled in a similar way.

Like in calculation of the root surface area, the length of the root grade studied was found by multiplying the respective tabulated length by the volume of the root. Finally, the values of the root surface area and length for each grade were summed up for every layer and horizon and referred to a surface area of 1 sq m.

Investigations made by Rustamov (1968) in north-western Turkmenia from 1961 to 1966 showed that studies of the productivity of the underground part of desert communities by the monolith method alone would be insufficient because it extends over a much greater area than the above-ground part. The entire above-ground part of a wormwood shrub may be confined to the area of a single monolith (0.25 sq m), whereas the underground part extends far beyond it. Owing to this, the measurements will cover practically the whole above-ground part and only part of the underground portion.

The most expedient technique for determining the total productivity of root systems and establishing the true ratio of the above-ground part to the underground part in desert communities is the estimation of the root mass in the entire nutrition area of plants. It has already been mentioned that this technique was suggested by Bazilevich and Rodin (1956) and worked out in detail later by Rustamov (1965, 1967). It should only be pointed out that data on the ratio of the above-ground to the underground parts differ with the method used (either the monolith or the nutrition-area method). That is why we are inclined to believe that both methods, one supplementing the other, should be used in studying the productivity of root systems in desert communities (Rustamov, 1968).

Treatment of Data Obtained

Rogers and Vyvyan tabulated the results (numerical data) of their extensive and detailed investigations, the upper value indicating the weight of skeletal roots, and the lower one, the weight of small roots, including the absorbing roots (in grammes) according to the soil horizons (down to the maximum depth of penetration). An example of this is shown in Table 16, while the arrangement of material obtained by the monolith (block) method is demonstrated in Tables 17, 18, 19, and 20.

Table 16

Weights of Roots of an Apple Tree on Paradise Rootstock No. IX (Horizontal Spread of Roots) after Rogers and Vyvyan

	26 8	71 10	18 6	20 7	8 4	15 5	7 3	4 1	6 4
	50 10	41 8	75 11	74 8	19 8	37 8	35 8	10 4	11 4
	24 9	40 12	67 14	87 9	82 13	37 8	32 7	43 7	18 6
15 1	67 15	116 19	70 17	383 18	163 17	50 9	73 9	40 8	11 5
	23 6	137 20	363 23	815 20	449 23	131 11	32 8	25 10	9 5
3	34 7	77 14	154 18	696 18	215 20	91 19	45 8	22 9	18 9
	47 14	21 8	22 6	47 8	80 8	88 14	51 10	22 8	19 10
	32 13	13 7	7 5	12 4	25 3	47 5	36 6	11 6	8 4
1 1	13 8	15 8	11 6	9 4	10 4	30 8	15 6	15 6	5 3
2 2	10 7	7 5	5 4	13 5	10 6	7 3	19 5	8 5	8 4

Note. The small squares represent columns of soil, 50 cm square in cross-section extending vertically down from the surface of the ground to the solid rock. The upper value denotes the total weight (in grammes) of roots found in that column; the lower value denotes the number of grammes of fibre roots (less than 1 mm in diameter) in the column. The small circle in the centre of the table indicates the location of the tree trunk.

Later they simplified the monolith method, owing to which the performance summaries became simpler too; their specimens are given in Tables 21 and 22.

Table 17

Actual and Relative Weights of Roots of Different Grades

	Actual Weights			Percentages		
Rootstock No.	I	I	IX	I	I	IX
Row No.	1	7	7	1	7	7
Tree No.	3	1	3	3	1	3
Grade	gms	gms	gms			
I less than 1 mm in diameter	1,963	628	808	14.0	13.3	13.3
II 1 mm to 2 mm	1,576	583	1,107	11.2	12.4	18.1
III 2 mm to 4 mm	1,574	597	884	11.2	12.5	14.6
IV 4 mm to 8 mm	2,258	1,203	1,013	16.1	25.4	16.5
V 8 mm to 16 mm	2,667	927	924	19.0	19.5	15.3
VI 16 mm to 32 mm	2,425	649	782	17.3	13.7	12.8
VII 32 mm to 64 mm	1,568	152	575	11.2	3.2	9.4
Total	14,031	4,739	6,093	100.0	100.0	100.0

Schitt (1936) and his colleagues recorded their data by representing the root density as shaded squares with the numerical data shown in the centre, and marking the spread of the root system, i.e. the amount and length of the skeletal roots (Fig. 40).

Kabluchko, Popova, and Kaimakan (1950) excavated an apple tree of the Golubok Dnestrovsky variety (on wild apple tree rootstock) growing on hard loamy soil of the Dnestr area (Moldavia) and found that the root system was quite vigorous and its distribution in the soil horizons was relatively regular; 19.6 per cent of the root spread occurred at a depth of 21 to 40 cm, whereas 51.7 per cent of the roots by weight was found at a depth of 41 to 60 cm. The root weight decreased from the stem to the branch spread periphery, while the spread increased.

To facilitate the comparison between the data obtained, Budagovsky (1948) estimated the root mass per sq m

Table 18

Weight of Roots of Ten-Year-Old Lane's Prince Albert Apple Trees on Different Rootstocks

Rootstock No.	Row No.	Tree No.	Year of Excavation	Weights of Roots							
				less than 1 mm in diameter		1 to 4 mm		4 mm and more		Total	
				g	%	g	%	g	%	g	%
IX (very dwarfing)	7	1	1927-1928	628	13.3	1,180	24.9	2,931	61.8	4,739	100
	7	3	1927-1928	808	13.3	1,991	32.7	3,294	54.0	6,093	100
			and so forth								

Table 19

Percentages of Root Weight in Different Depths on Loam Soil

Rootstock No.	IX				II			
Row No. Tree No.	7 1		7 3		1 6		1 7	
	all roots	fibre alone	all roots	fibre alone	all roots	fibre alone	all roots	fibre alone
Total weight (g)	4,739	628	6,093	808	14,561	959	15,788	1,101
Percentages (by weight):								
Depth:								
0-17 cm	9	10	7	18	7	14	8	12
17-34 cm	40	14	40	15	47	15	39	18
34-50 cm	11	9	20	11	13	10	19	9
50-100 cm	25	36	15	23	25	44	21	39
100-150 cm	12	24	13	22	8	17	13	22
150 cm and more	3	7	5	11	—	—	—	—
deeper than 34 cm	51	76	53	67	46	71	53	70
deeper than 50 cm	40	67	33	56	33	61	34	61

Table 20

Summary of Performance of Trees. Lane's Prince Albert Planted on Different Rootstocks

Rootstock No.	IX	I
Row No.	7	1
Tree No.	1	3
Excavation time	January, 1928	
Tree age (years)	10	10
	grammes	
(a) Weight of branches and trunk when lifted	12,200	27,100
(b) Weight of prunings to date	1,701	4,590
(c) Total stem growth weight	13,901	31,690
(d) Total root weight	4,739	14,031
(e) Total stem and root weight	18,640	45,721
(f) Total weight of fruit	58,600	77,600
	ratios	
(g) $\frac{c}{d}$ $\frac{\text{Total stem}}{\text{Roots}}$	2.93	2.26
(h) $\frac{a}{d}$ $\frac{\text{Stems (as lifted)}}{\text{Roots}}$	2.57	1.93
(j) $\frac{f}{e}$ $\frac{\text{Fruit}}{\text{Total tree weight}}$	3.14	1.70
(k) $\frac{f}{d}$ $\frac{\text{Fruit}}{\text{Roots}}$	12.4	5.53
(l) $\frac{f}{c}$ $\frac{\text{Fruit}}{\text{Total stems}}$	4.22	2.45

each quadrant. Examples of this are shown in Tables 23 and 24.

Ivanova (1957) examined a gooseberry root system in the Moscow Region by the monolith method and obtained valuable information, which she recorded as demonstrated in Table 25.

Table 26 shows how Voronchikhina (1956) recorded her findings.

An example of the form used for drawing up data obtained at the Pomology Department of the Timiryazev Academy from studies of the root system of apple trees in eight age periods (Krestnikov, 1964) is given in Table 27.

Table 21

Effect of Rootstock on Stem-to-Root Ratio and on Depth of Rooting

Rootstock No.	IX		II	
Row No.	9	9	2	2
Tree No.	4	5	1	2
	grammes			
(a) Stem weight (trunk and branches)	917	843	1,360	1,751
(b) Root weight	939	942	1,907	2,298
Ratio $\frac{\text{Stem weight}}{\text{Root weight}}$	0.98	0.89	0.71	0.76
Percentage of root weight:				
above 30 cm	81.6	93.8	—	79.6
below 30 cm	18.4	6.2	—	20.4

Table 22

Depth of Rooting of Ten-Year-Old Lane's Prince Albert on Heavy Clay Soil

Rootstock No.	II	I
Percentage in depth:		
0-30 cm	50.2	53.7
30-50 cm	40.2	24.6
50-100 cm	9.6	21.6
Below 100 cm	—	0.1
Total root weight, grammes	7,177	8,592

Evaluation of the Method and Examples of Its Application

Excavation of the whole root system or even of a small part of it by the monolith method yields a comparatively true picture of the distribution of both skeletal and small roots. The method is especially suitable for studying the effect of various soil management techniques. This method can be applied independently or in conjunction with others, particularly with the skeleton method.

If the roots have been thoroughly unearthed by the skeleton method there is no need to supplement it with the

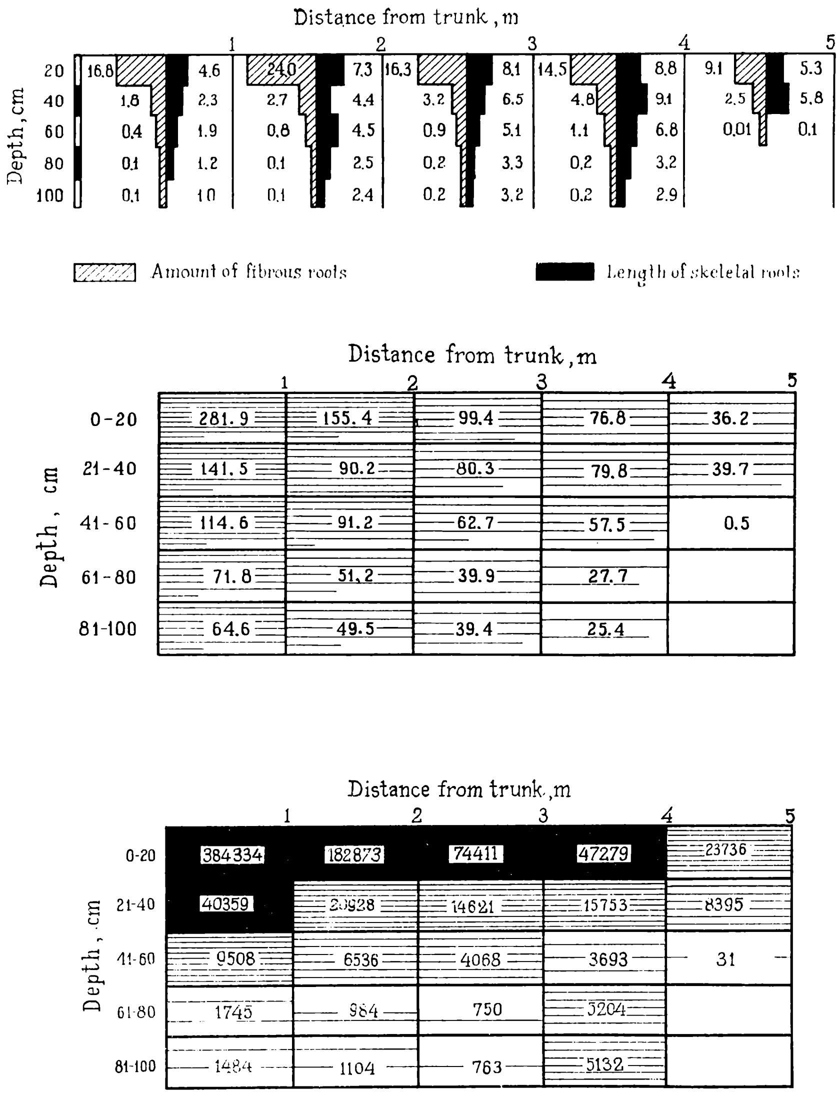


Fig. 40. Distribution of the root system of Antonovka apple grafted on plumleaf crab apple (*M. prunifolia*) growing on weakly degraded loamy chernozem (top); stand-thickness of skeletal roots (middle) and fibrous roots (bottom) (after Schitt)

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Table 23

Weight of Roots of Two-Year-Old Apple Tree Seedlings per Quadrant in Relation to Rootstock and Variety Grafted (after Budagovsky, 1953)

Rootstock	Age of tree (years)	Root Weight											
		Quadrant I				Quadrant II				Total			
		all roots		roots of diameter less than 2 mm		all roots		roots of diameter less than 2 mm		all roots		roots of diameter less than 2 mm	
		g	%	g	%	g	%	g	%	g	%	g	%
					Antonovka Variety								
III	2	14.3	97.94	4.9	33.56	0.3	2.06	0.3	2.06	14.6	100.0	5.2	35.62
					and so on								

Table 24

Root Length per Quadrant in Relation to Rootstock and Variety Grafted (after Budagovsky, 1953)

Rootstock	Age of tree (years)	Root Length											
		Quadrant I				Quadrant II				Total			
		all roots		roots of diameter less than 2 mm		all roots		roots of diameter less than 2 mm		all roots		roots of diameter less than 2 mm	
		mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
						Antonovka Variety							
III	2	4,889	95.08	4,770	92.76	253	4.92	253	4.92	5,142	100.0	5,023	97.68
						and so on							

Table 27

Density of Fibrous Roots in Subsoil at Various Distances From Trunk of Antonovka Obyknovennaya Apple Trees of Different Age

Age periods and actual age (years)	Length (m) of roots of various diameters (mm) in identical soil volumes (50×100×100 cm) at various distances from trunk											
	1 m				3 m				5 m			
	5-3	3-2	2-1	1-0.5	5-3	3-2	2-1	1-0.5	5-3	3-2	2-1	1-0.5
	Antonovka Obyknovennaya											
I-4	—	0.6	1.9	6.9	none	none	none	none	none	none	none	none
II-8	—	1.2	7.2	75.4	none	none	none	none	none	none	none	none
III-14	3.6	2.9	5.6	31.1	0.8	1.7	6.7	**90.4**	none	none	none	none
IV-26	3.7	11.2	20.3	166.4	3.2	2.6	4.1	37.7	0.5	1.2	4.4	19.8
V-52	8.2	8.7	8.1	66.5	5.6	9.7	15.7	**70.1**	0.5	3.6	5.0	10.5
VI-58	7.7	15.5	11.4	47.4	4.2	13.5	11.0	56.3	1.8	11.2	9.6	**62.1**
VII-58	7.4	18.2	40.5	**171.7**	5.2	5.7	15.0	31.0	1.7	6.7	10.1	41.8
VIII-50	4.6	7.2	5	11.8	4.1	11.7	13.1	**62.8**	0.9	3.9	2.1	2.8

Table 25

Total Weight of Roots of Gooseberry Shrub (actual weight from one quadrant), g

Horizons	Zone, cm					Total	
	0-25	25-50	50-75	75-100	100-150	g	% of total
Above 0	15.40	12.87	5.34	1.30	—	34.91	4.0
0-10 cm	54.41	110.12	20.05	14.92	1.71	201.21	23.1
10-20 cm	26.50	127.42	119.10	68.94	12.20	354.16	40.6
20-40 cm	16.82	35.91	34.65	24.25	24.42	136.05	15.6
40-60 cm	10.71	18.04	17.88	21.47	12.56	80.66	9.3
60-80 cm	9.82	19.38	13.71	12.45	9.57	64.93	7.4
Total, g	133.66	323.74	210.73	143.33	60.46	871.92	100.0
% of total	15.3	37.1	24.2	16.4	7.0	—	100.0

Table 26

Distribution of Roots of Six-Year-Old Finik Gooseberry, g

Soil horizons	Sample No.	Depth of monolith removal, cm	Grade according to root diameter, mm			
			less than 1	1-3	more than 3	total
A_0	1—4	0-10	1.230	2.880	12.300	16.410
A_1	5—8	10-30	4.774	17.010	38.390	60.174
A_2	9—12	30-50	1.880	7.365	1.680	10.925
B_1	13—15	50-70	2.160	1.990	—	4.150
B_2	17—20	70-90	0.960	2.580	—	3.540
		Total	11.004	31.825	52.370	95.199

monolith method; the whole root system can simply be drawn on a plan showing the extension of all roots in depth and in the radial direction towards the branch spread periphery and beyond it. This will give a pretty clear idea of the spread of skeletal and small roots.

At present, many researchers use only simplified methods and believe that there is no need to wash out the whole root system of fruit plants or even berry plants.

All those employing the monolith method attempt to record the "active", or absorbing, roots separately from the remaining "inactive", or conducting, roots which are incapable of absorption. They base their classification on root thickness. For instance, Rogers and Vyvyan (1934), Batalov (1952), and Galushka (1956) included in the active group all roots 1 mm in diameter, while Dragavtsev (1938) and S. S. Rubin (1954) included 2-mm roots in that group. Muromtsev (1948) considered all black currant roots

not thicker than 4 mm as active. Rogers and Vyvyan (1934) found that 60 per cent of apple tree roots were less than 1 mm thick and classified them as fibrous.

Roots up to 1 or 2 mm thick should not be included in the "active" group because most functioning roots are 2 to 3 mm thick, while most of the "inactive" roots have a diameter of 1 to 2 mm. We believe that there are two ways of solving the problem: firstly, by determining the relative weight of only the "active" parts of the roots, which can be done immediately after excavation and washing by examining all root nets and measuring all roots, the "active" ones among them. They can be detected by the translucent white colour of the absorbing roots, as is done in the "free monolith" technique.

The second way is to separate all small grade roots, including both "active" and "inactive" ones, i.e. all those of diameter up to 3 mm or so. This grade, which can readily be isolated, will characterize the bulk of these roots and their distribution in the soil and from the trunk towards the periphery of the branch spread. In certain periods of the vegetative season, usually in the spring and also in the autumn (if humidity is high enough) the roots of this grade may consist predominantly (up to 70 and even 90 per cent of their length) of "active" (absorbing) roots.

Therefore, to simplify the procedures in excavating a root system it seems reasonable to restrict oneself to recording all the roots *en masse*, i.e. both "active" and "inactive", assuming them to be potentially valuable. With changes in the conditions, for example after watering, rains, harvesting, leaf fall, etc., these roots may rapidly form a multitude of "active" roots, with only 10 to 20 per cent of the entire length of the plant root system remaining "inactive".

CHAPTER 5

THE TRENCH (PROFILE) METHOD

Specific Features and Purpose

The trench, or profile, method consists in digging a trench at a certain distance from the trunk within the soil containing the root system, down to the maximum depth reached by the horizontal roots, marking off the root tips (seen on the soil face) on a plan, and recording their amount and thickness. The soil horizons are also shown on the same plan. Such a plan (or a drawing, or a photograph) not only illustrates the cross-section of the roots, i.e. their distribution in the horizons, but also makes it possible to estimate their amount for comparing root growth under different soil conditions.

Thus, the method of cutting roots at a vertical trench wall permits one to determine the distribution of the horizontal roots in the soil horizons at various distances from the trunk and with respect to the branch spread in order to reveal the effect of soil conditions, rootstock, and cultural measures (the depth of soil cultivation, application of fertilizers, irrigation).

This method is convenient for determining the depth of penetration of horizontal roots and for recording small roots about 1 mm in diameter, i.e. the density of the absorbing roots in the soil.

A prototype of the profile method was the original Hellriegel method (1883). A bottomless cylinder with a sectional area of 400 sq cm was driven into the soil to the required depth, the soil was cut at the cylinder base and the amount of roots (their tips) exposed at the soil section was estimated. Weaver (1913) proposed a technique for studying plant roots on vertical walls of trenches. He freed the roots from soil over the entire trench wall to a depth of 10 mm and made a sketch of them on graph paper. The profile method was

employed most widely by Oskamp and Batjer (1932) at the New York Agricultural Experimental Station. Later scientists in the USSR and other countries introduced a number of modifications into the method.

The profile method proves particularly valuable: (1) in approbation of lands intended for orchards; (2) for revealing certain obscure unfavourable phenomena in orchards; (3) as an auxiliary to the skeleton method.

Techniques of Root Excavation

The procedure of the profile method is as follows:

(1) preparation of a trench of a definite length, width, and depth;

(2) cleaning the trench wall for better inspection of the root spread and of the root diameters, and for easier detection of the soil horizons;

(3) marking the roots (to a scale) on a plan, and

(4) recording the roots according to thickness, depth of penetration, and soil horizons.

Oskamp and Batjer (1932) used this method for studying the fitness of vast territories for fruit growing, so their work was in the nature of field research. At first they made a careful study of the soil by drawing samples from a depth of down to 1 or 2 m under every third tree of every third row. After 92 orchards had been examined in this manner, areas typical as to soil and other conditions were selected for more detailed examination.

The trenches were arranged at a distance of 3 m from the trunks for old trees and 2 or 1 m for younger ones. A trench was shaped like a rectangle 3 m long, 60 cm wide, and 60 cm deep. First the soil was removed in 20-cm layers and placed on a sorting table, where the roots were freed, grouped into five thickness classes, and weighed. Thus, the authors employed the monolith method with dry sorting of roots as an auxiliary to the trench method. Such techniques of orchard studies were mostly applied only to a depth of 40 cm, where the bulk of horizontal roots were usually distributed. Then the vertical trench wall with the root tips visible on it was exposed. The roots were cut off strictly along the vertical wall and marked to a scale on the plan; their thickness and position on the soil section were recorded. The roots were represented on the plan by dots varying

in size with root diameter. The root grades were grouped according to diameter as follows: (1) less than 2 mm, (2) 2 to 5 mm, (3) 5 to 10 mm, (4) 10 to 20 mm, (5) 20 to 30 mm, (6) 30 to 40 mm, and (7) more than 40 mm. The soil horizons were also marked on the plan. Soil samples were taken for further studies and tests. Oskamp and Batjer maintained that the plans served as valuable illustrative material characterizing the distribution of roots in various soil horizons. From the information gained they made some valuable suggestions concerning the selection of the best lands and improvement of the agricultural techniques of fruit growing.

Modifications and Simplifications

Artyukh (1935) proposed some modifications to the method of Oskamp and Batjer. He suggested that the top layer of the soil surrounding the trunk of the tree chosen for excavation should be removed carefully within a radius of 0.5 to 1 m, which would permit selecting a quadrant with an average amount of roots for the given tree. This selection technique is undoubtedly expedient, particularly if it is impossible to excavate several root systems.

Dragavtsev (1936, 1956) made the following modifications. A 60-cm wide trench was dug on the north-eastern side of the tree from the periphery of the branch spread towards the trunk, and to the depth of penetration of horizontal roots. It was driven in consecutive sections 1 cm long and the walls facing the trunk were trimmed smooth with a spade. This method, which enabled the author to record the spread and distribution of roots of various thickness in the soil at intervals of 1 m from the periphery towards the trunk, was later used mostly for additional root excavation during field studies.

Since 1952 the trench method has been used on an ever-increasing scale at the Pomology Department of the Timiryazev Academy in studying the fruit plant root system. It is important that in exposing the roots the trench walls should be strictly vertical. Before the roots are marked off on the plan, the trench wall should be refreshed (to a depth of 3 or 5 mm) with a small sharpened stick or with some other instrument (grapnel) so that all the roots, thin ones

in particular, would be more visible. After this the trench wall is divided into 10-cm squares with a pointed stick, or with the aid of a special frame (with 1-m walls) made of thin wires forming 10-cm squares which are placed against the entire profile or part of it. Either procedure greatly facilitates marking off the roots on the plan.

To improve the modifications of the profile method proposed by Oskamp and Dragavtsev and the modification of the skeleton method, Devyatov (1960) employed the technique of arcuate trenches. He set off a quadrant or octant of the circle surrounding the trunk and divided it into zones along which two concentric trenches 2 m deep and 1 m wide were driven. The first trench was run so that its walls were spaced 1 m and 3 m from the trunk, respectively. As a result, vertical walls comprising one-fourth or one-eighth of the circumference were formed at distances of 1, 2, 3, and 4 m from the trunk. The distribution of roots in the soil layers, both in the horizontal and vertical directions was determined from these sections.

Vashchenko (1965) studied the root system of apple trees growing on the shore sands of the Don by the trench (profile) method. He examined five trees on a sample plot by digging four trenches 1 m long and 1 m wide in all four cardinal directions from the central tree. The trenches were 1.2 to 1.5 m deep and were dug perpendicularly to the horizontal roots radiating from the trunk. In this way nine vertical 1-m wide walls were formed at distances of 1, 2, 3, 4, and 5 m from the tree with 10-m inter-row spaces, or seven walls with 8-m inter-row spaces, or five walls with 6-m inter-row spaces. Roots were recorded from these walls on all four sides, so that all the roots of the central tree could be counted (i.e. from the North, South, West, and East). For the remaining four trees, only roots from one of the sides (North for one, South for another, East for the third, and West for the fourth) were counted. Records for two complete trees were thus obtained, clearly showing the total amount of roots and their density in the different segments of the soil surrounding the trunk.

So as to minimize the damage to the tree by excavations, the trenches were sunk one after another. First one trench was driven, and after recording the amount of roots in it was refilled with earth (and sometimes watered), then the next trench was driven, and so on. The roots on the vertical

trench wall were recorded in 10-cm layers according to the genetic soil horizons, but previously they were slightly exposed with a peg (awl) by sinking it 2 to 3 cm into the wall. The recorded roots were marked off on graph paper to a scale of 1:10, indicating the genetic soil horizons. Roots thinner than 1 mm were shown as dots, those 1 to 3 mm thick, as small circles, those 3 to 10 mm thick, as small circles with a dot in the centre, and roots thicker than 10 mm, as black circles.

Thus, combining excavation of the roots with their representation on the plan, removal of a monolith, and quantitative recording of the roots by the profile method, Vashchenko described every trial plot.

Later not only the horizontal but also the vertical distribution of roots and the worm holes was studied at the Pomology Department of the Timiryazev Academy (Kulenkamp, 1966). Trenches 50 cm deep, 100 cm long at the bottom, and 50 cm wide were driven a given distance from the trunks of fourteen-year-old Antonovka and Anis apple trees on three rootstock varieties and in three variants of ploughing. A 50×50 cm area of the trench floor was cleared and covered with a 50×50 cm metal frame, on which wires were stretched in two directions at 10-cm intervals forming twenty-five 100-cm squares. After removing the top layer of soil from the squares with a knife, the number of vertical penetrating roots and the number of worm holes not occupied by them were counted.

The grid can be drawn right on the soil with a knife, cutting straight lines with a ruler at intervals of 10 cm. At a depth of 90 cm the floor of the same trenches was cleared again and the numbers of vertical roots and worm holes counted, thus determining the vigour and extent of branching of the vertical roots. The data obtained were marked on graph paper to a 1:10 scale, the roots being denoted by conventional symbols.

In this technique the roots were excavated at distances of 90 to 140, 250 to 300, and 350 to 400 cm from the trunk at depths of 50 and 90 cm. It was found that with twelve- to fourteen-year-old apple trees growing on soddy-podzolic soil vertical root growth occurred only within the boundaries of the branch spread and only fibrous roots grew downwards beyond this zone, whereas the spread of horizontal roots was one-and-a-half times the branch spread. Deep

ploughing facilitated the growth of horizontal roots in deeper horizons, but exerted almost no effect on the growth of vertical roots.

The profile method yields accurate information on the extent of development of vertical roots and their distribution, which is especially important in such work as deep loosening of a fruiting orchard, introduction of fertilizers to a great depth, and primarily in straight or repeat ploughing.

A simple and rapid method for preparing profiles for examining the root system of trees was also worked out, for which a tractor was adapted.

As evident from the foregoing, the distance between the trenches and the trunk and the number, length, width, and depth of the trenches vary with the purpose and object of study, the number of replications, the variants, and the methods employed. Examination of the root system of a berry plant or of a young fruit plant can be successfully accomplished from a single trench driven 0.5 to 1 m from the trunk, whereas in the case of a fruiting tree three to five or even more trenches must be driven 1, 2, 3, 4, 5 or more metres from its trunk, depending on its age, size and the purpose of the investigation.

In approbation of large territories for orchards one or two trenches are dug per tree, but a larger number of trees are studied on the chosen area. The trench must be deep enough to include the entire horizontal root spread. For example, in the soddy-podzolic soils of the Moscow Region the horizontal roots of an apple tree extend to a depth of 75 cm, those of a pear tree to 50 cm, sour-cherry tree 40 cm, and plum tree only 30 cm.

Treatment of Data Obtained

The main task is the most accurate rendering of root distribution in the soil on a plan, showing the thickness of the roots to scale. This is usually done on graph or plain paper fastened to a sheet of plywood. The paper is ruled to a 1:10 scale or into smaller squares and the genetic soil horizons are marked on it. The roots are shown as dots, small circles, circles with a dot in the centre, etc. (for example, a dot designates roots 1 to 3 mm thick; a circle, those 3 to 8 mm thick; and a circle with a dot, roots thicker

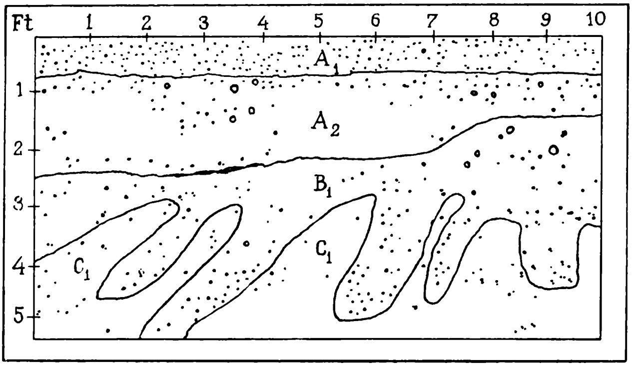


Fig. 41. Root distribution in the genetic horizons of type No. 22 soil:

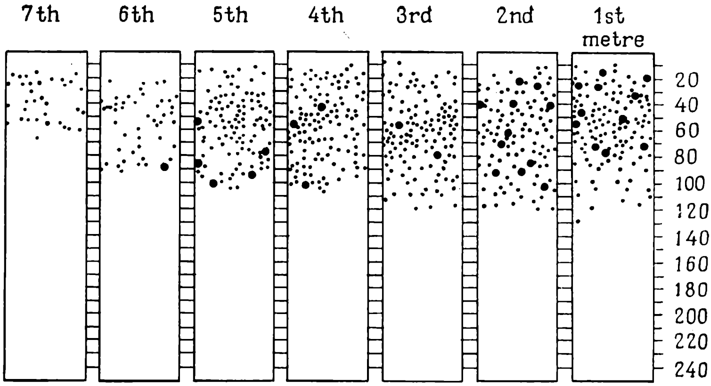
A_1—light, brown sandy loam; A_2—yellowish loamy sand, slightly spotted with a greyish hue, rather compact; B_1—dark-brown clay, hard; C_1—brown or compact. Many roots are seen in B_1 clay layers, invading C_1 horizon from the slimy layer. This illustrates the irregular and wave-like pattern of the genetic soil horizons (after Oscamp and Batjer)

than 8 mm).There may be a larger number of root grades. Sometimes roots are shown as dots of various size. The plan can be drawn by one person, but it is advisable to work with an assistant.

Below we give several drawings by way of an illustration. Oskamp and Batjer (1932) marked the roots on the plan as dots varying in size according to the root thickness (Fig. 41). The drawing shows the distribution of the roots in the genetic soil horizons.

Dragavtsev (1936, 1956) represented very pictorially (Fig. 42) the valuable information obtained by him in his studies of the root system of fruit plants in the Caucasus and Kazakhstan by the trench method.

Records (E. V. Kolesnikov, 1953) of the roots of apple trees growing in the orchard of the Timiryazev Academy made from the walls of three trenches spaced 1, 2, and 3 m from the trunk showed that the top 10-cm layer of soil often did not contain any roots. Very thin roots (thinner than 1 mm, mostly absorbing roots) of 11-year-old apple trees were recorded separately according to the soil horizons (Table 28).



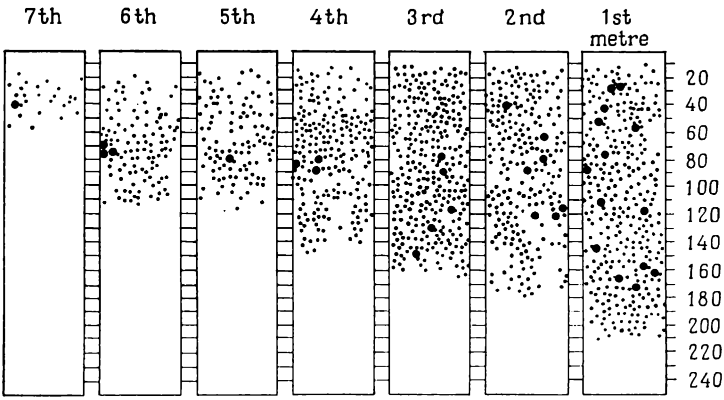


Fig. 42. Effect of gravelly deposits underlying mountain-steppe chestnut soil on the distribution of the root system of a 15-year-old Apport apple tree in Kazakhstan (the root tips are seen on the walls of trenches driven from the periphery to the trunk, from the seventh to the first metre).

Top row—soil profiles with gravelly layer at a depth of 130 cm; bottom row—soil profiles without gravelly layer (after Dragavtsev)

There were 132 roots per tree on the average in horizon A_1 and only 29 in the podzolic horizon A_2, the ratio being 5:1. Only 23 roots were found in the 20-cm transitional horizon. If an entire segment (quadrant) were excavated to determine the total amount of roots, then at a distance of 1 m from the centre of the tree the trench would have to be

Table 28

Distribution of Roots Less Than One mm in Diameter on Walls of Trenches Dug Near Apple Trees of the Osenneye Polosatoye, Slavyanka, and Kitaika Zolotaya Varieties (Timiryazev Academy, 1953, average data for 11 trees)

Horizons	Depth, cm	Number of roots at various distances from stem			Total
		1 m	2 m	3 m	
A_1	10-26	88	40	4	132
A_2	26-42	15	12	2	29
A_2/B_1 (transitional)	42-61	15	6	2	23

Table 29

Number of Root Tips per Quadrant Excavated (Timiryazev Academy, 1953, after Kolesnikov)

Horizons	Number of roots at various distances from the trunk			
	1 m	2 m	3 m	1-3 m
A_1	146	125	20	291
A_2	25	38	10	73
A_2/B_1 (transitional)	25	19	10	54

1 m long, at 2 m from the centre 2 m long, at 3 m from the centre 3 m long, and so on. Some researchers follow this pattern. Kolesnikov found that in horizon A at distances of 1 and 2 m from the trunk there were 146 and 125 roots, respectively, in the podzolic horizon 25 and 38, while at a distance of 3 m from the trunk the roots were considerably fewer in number (Table 29).

Root records showed that in the podzolic soils of the Moscow Region the main mass of absorbing roots was confined to the top accumulative-humus horizon, the richest in nutrients and, in addition, the most efficiently aerated and warmed.

Garyugin (1955) examined the vertical roots of some fruit species and obtained interesting information on the downward growth of roots; his findings are also of methodical interest (Table 30).

The Number of Tips of Vertical Roots at Various Depths (after Garyugin, 1955)

Depth of layer, cm	Number of tips, per 1 sq m						
	apricot	cherry-plum	sour cherry	walnut	plum	mulberry	apple
100	46	51	62	54	43	54	41
150	35	33	63	44	37	55	43
200	40	24	69	43	36	59	43
250	58	30	56	46	—	56	49
300	28	41	66	55	—	65	40
350	35	50	58	51	—	59	47
400	40	62	64	43	—	68	57

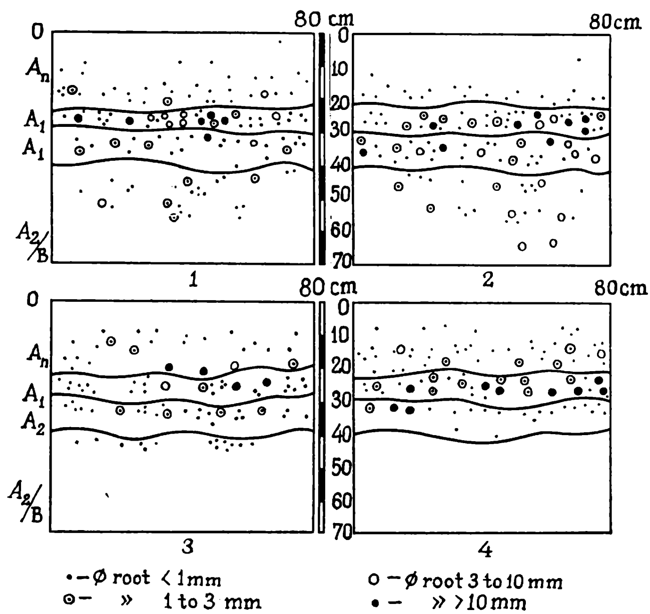


Fig. 43. Distribution of horizontal roots in 14-year-old Antonovka Obyknovennaya apple on rootstock:

1—Antonovka Obyknovennaya seedlings; *2*—wild apple; *3*—Doucin III; *4*—Chinese apple seedlings. Timiryazev Academy orchard (after Ghena)

The distribution of horizontal roots of plum trees and apple trees (Ghena, 1957) was studied at the Pomology Department of the Timiryazev Academy. The results, registe-

Table 31

Distribution of Apple Tree Roots in Soil Horizons (per cent of total number) (after Zemlyanov, 1959)

Soil horizon and depth of root penetration, cm	Variety				
	Ranetka Purpurovaya seedling (control)	Grushovka Moskovskaya	Papirovka	Borovinka	Antonovka Obyknovennaya (etc.)
Top horizon					
A_1 0-10	16.2	16.5	11.5	18.8	17.7
11-20	41.2	30.1	23.1	22.1	19.5
21-29	33.5	34.9	27.8	26.5	31.9
Intermediate					
A_2B 30-40	7.4	8.9	20.7	17.4	19.5
etc.					
Total number of roots with exits in the trench	179	146	183	106	113
Branch spread, m	—	1.3	1.26	1.3	1.3

Table 32

Spread of Thin Apple Tree Roots on Thick Loess-Like Loam (30-Year-Old Tree, Byelorussia) (after Rezvyakov, 1963)

Horizon	Depth, cm	Number of roots per 1 sq decimetre of vertical wall at various distances (m) from trunk							% of roots in horizons
		1	2	3	4	5	6	1-6	
A_1	10-30	9.83	13.25	10.18	7.21	4.69	1.75	7.80	57.3
A_2	30-50	2.78	3.40	3.09	3.15	2.16	1.49	2.68	22.4
B_1	50-100	2.40	1.04	0.84	0.84	0.52	0.05	0.45	14.3
B_2	100-150	1.24	0.88	0.22	0.28	0.15	—	0.46	6.0
	10-150	3.10	3.06	2.27	1.88	1.22	0.48	2.00	—
% of roots along circumference		9.5	18.8	21.0	23.1	18.8	8.8	—	100.0

red as shown in Fig. 43, characterized the reciprocal rootstock-scion influence.

Of interest are the studies themselves, conducted in the Gorky Region (Zemlyanov, 1959) and in Byelorussia (Rezvyakov, 1963), and the elements of root recording in these works (Tables 31 and 32).

Reznichenko obtained valuable information (1964) from

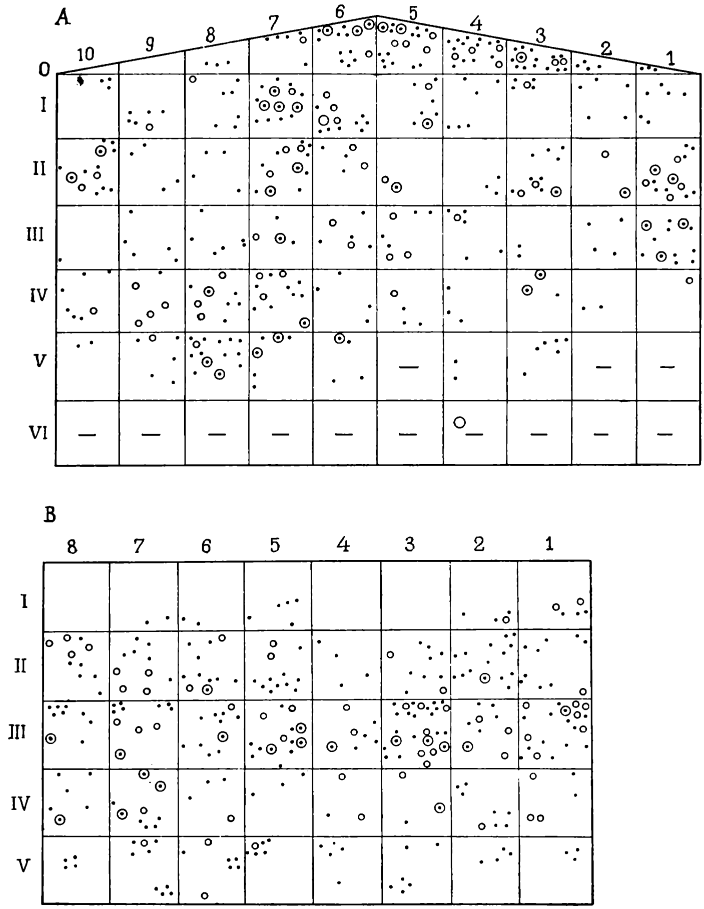


Fig. 44. Distribution of the root system of a 6-year-old currant shrub within a radius of 25 cm (*A*) and 70 cm (*B*) from its base.

A circle with a dot indicates roots thicker than 3 mm, an empty circle indicates roots 1 to 3 mm thick, and a dot indicates roots thinner than 1 mm (after Reznichenko)

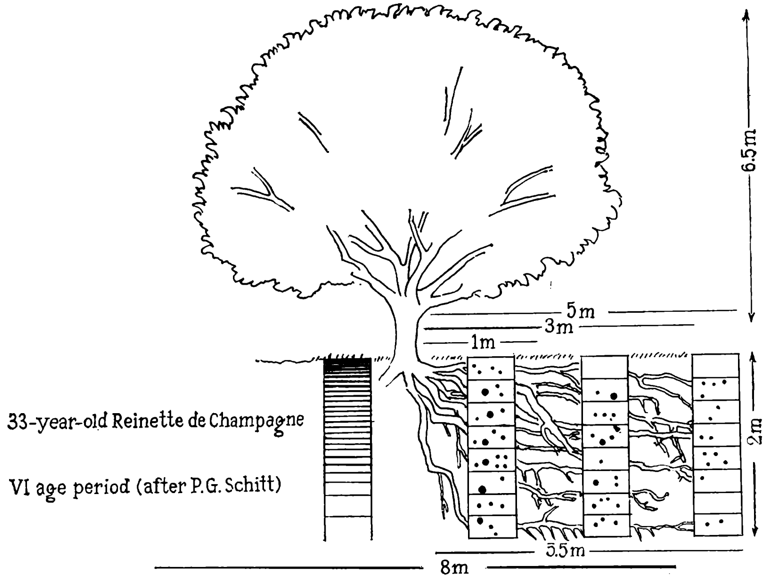


Fig. 45. Reinette de Champagne apple on wild apple rootstock. The roots are represented as seen on excavation by the skeleton and profile methods (after Krestnikov)

studies of currant and gooseberry root systems by the profile method. He showed that in the podzolic soils of the Moscow Region (Timiryazev Academy orchard) most of the root system of fruiting currant shrubs penetrated to a depth of 50 cm, and that of gooseberry shrubs, to 60 cm. These findings are represented on a drawing (Fig. 44).

Krestnikov (1964) suggested that information gained in studies of a plant root system jointly by the skeleton and profile methods should be recorded on a single plan (Fig. 45) showing the spread of the horizontal roots and the depth of their penetration (the roots being denoted by dots). Such a drawing is extremely pictorial and convincing.

Evaluation of the Method and Its Applications

The trench method is extremely valuable in its own right and also when used as an auxiliary to all other methods. The researcher will save time, labour, and money by excavating a small number of trees by the skeleton me-

thod and making several times as many excavations by the profile method. Thus he will gain considerably more information on the root system, and the results of the studies will be more convincing. Moreover, the root system suffers less damage with the use of the profile method than with the skeleton technique, which involves removal of soil from a whole quadrant.

It is particularly expedient to use the profile method in field studies of new territories intended for fruit growing. Being less time- and labour-consuming and cheaper than the other methods, it also gives an adequate picture of the distribution of the bulk of the root system in the soil. Vast areas can be covered and convincing results obtained.

CHAPTER 6

METHOD FOR WASHING OUT ROOTS OF WHOLE PLANTS

Specific Features and Purpose

The method consists in washing out of the soil the whole root system of a fruit or berry plant, and is effected carefully so as to leave all the roots intact, the absorbing ones included. It is usually employed in studies of young fruit and berry species, not older than one or two years. The root system of older plants is examined by other, less laborious, techniques.

The method has been in use for a long time. Stockhardt (1855) employed it for studying the root growth of herbaceous plants under natural conditions. Later it was applied by Nobbe (1875), Heinrich (1876), Hellriegel (1883), Müntz and Jirard (1891), King (1893), Slyozkin (1893), Tanfilyev (1894), Sokolovsky (1898), Rotmistrov (1907), Modestov (1916), and many others.

King (1892) made wide use of it. He first dug out a prism 1 m long and 30 cm wide to a depth depending on the downward extension of the roots, and covered its top with a special cementing material to fix the root collars in place. Then he enclosed the prism in a metal net case and pierced it with parallel rows of wire rods to keep the roots in their natural position. The soil was gradually washed away by a water jet from a hose. The procedure is difficult, but it yields good results.

Modestov (1915) washed the roots free from a trench dug across the plant beds, using a fire hose. The work continued the entire vegetative season.

Some researchers (for example, Dehĕrain, 1893) sowed grasses on a slope raised 2 m over the field surface, then dug a trench, washed free the root system, and photographed the root pattern.

In 1898 Sokolovsky (1913) used the washing-off method in his studies of the depth and nature of the distribution

of roots of cereals. He excavated a soil monolith about 18 cm thick and 107 cm long and fitted over it a cylinder of galvanized netting with 6 mm mesh. Then he covered the monolith with earth and sowed plants on it. At the end of the experiment the monolith was unearthed, the netting taken off, and the roots freed from the soil with a jet of water.

Vorobyev (1916) pointed out that an appreciable amount of roots of cereals was lost during washing, but he believed that the method yielded valuable results.

Techniques of Root Excavation

We made wide use of the method of washing the roots free when studying the root systems of seedlings of orchard and wild varieties in the Crimea from 1920 to 1930.

The main operations are:

(1) digging a trench prior to washing out the seedlings;

(2) washing out the roots and freeing them;

(3) transporting the whole seedling together with the root system to the laboratory, and

(4) measuring the root length and recording the amounts of roots of all orders.

The seeds of fruit plants were sown on plots and left there for one to two years. During the first one or two weeks of growth the seedlings were taken together with the soil by

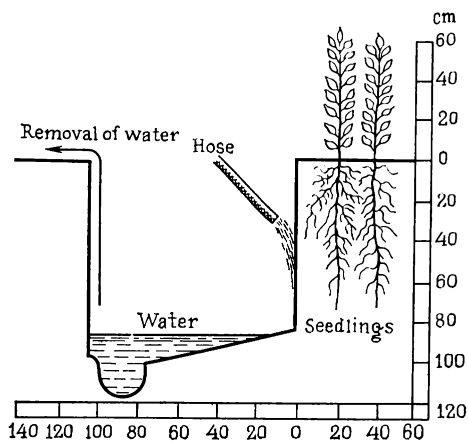


Fig. 46. Washing out apple tree seedlings (cross-section of bed)

means of a small trowel and washed free of soil in a pail of water. For later studies a trench with a vertical wall was driven across the plot in front of a row of seedlings. The floor of the trench sloped towards the wall opposite to the seedlings and ended in a small pit in which the water accumulated after washing and from which it could be gradually scooped out (Fig. 46).

The seedlings were previously tied to stakes driven in obliquely to support the root system and prevent it from sliding into the trench together with the water and soil, so that the roots were left hanging. Only the middle seedlings were washed, whereas the lateral (buffer) ones were discarded to neutralize more fully the effect of the free space (paths) between the rows.

At first a strong jet of water was aimed at the trench wall to expose the first seedling roots as the soil was washed off. After this the jet was reduced and the roots were freed gradually and patiently. It was noticed that water falling on the trench wall was absorbed extremely slowly because wet soil fell into the pit.

When washing was done with a small jet all the roots, the absorbing ones included, remained intact. This can be attributed primarily to the fact that the bulk of the root system does not lie very deep but is usually found in the humus horizon, where the soil is easily separated and washed off; besides, in the spring and partly in the early summer the seedlings are still small; secondly, the roots of fruit and forest trees are clearly more rupture-resistant than the roots of herbaceous plants. Many researchers who washed roots of herbaceous plants often emphasized that they were delicate and could be lost during the procedure.

We found that even absorbing roots, which were the least resistant to rupture, had a thickness of 1 to 3 mm, while those of a pear tree were even thicker. We did not lose any of the roots, even absorbing ones, in the course of washing, which convinced us that the whole root system can be washed free with water and remain intact (without breaks or ruptures).

After the seedlings had been washed out the next two or three rows of seedlings (buffer ones) were cut out together with the soil and discarded, then a wooden shield was put up against the exposed soil area, and the trench was filled with earth. In addition, before each washing procedure,

i.e. after ten to fifteen days, another one or two rows of plants (buffer) were discarded. The seedlings were discarded twice in order to reduce or completely eliminate the action of water that could have remained after the procedure, or the effect of a dried soil surface. Shields were used only at the end of the summer and in the autumn, while in the spring and in early summer, when the seedlings were small, the trenches left after washing were filled with earth. The method of freeing the roots by washing involves hard and tedious work and requires a lot of patience.

Modifications of the Method

Pushkarev (1925) and Sokolovsky (1913) grew plants in soil monoliths placed in boxes and covered with earth. Consequently, the plants grew in conditions close to natural. They could then be taken to the laboratory and the roots washed out there instead of in the field, at any moment of the vegetative period and with less expenditure of labour, time, and money.

Tsivinsky (1933) began the washing with the tap root and proceeded until the lateral branches were exposed. After this exploratory procedure he washed the lateral branchings of the first and subsequent orders. To prevent the rupture of the delicate thin roots and to facilitate the process, he made holes with a needle along their path.

As the roots were exposed they were marked on a plan to an accepted scale. After the root system had been excavated the ratio of the length of the active (absorbing) roots to that of the inactive (conducting) roots could be established.

Terekhova (1954), when washing the root system, exposed the roots along their entire length by means of a sharp instrument (awl). Zakotin and Nikitochkina (1967) grew the seedlings in nurseries and removed them without disturbing the root system. They used a hood (box) of sheet iron with 3-mm walls. Its size depended on the method of seedling cultivation: with single-row sowing on the sod-dy-podzolic soils of the Moscow Region the base could reach 40 cm in width; the length depended on the number of plants used in the studies but was not more than 50 cm. With double-row or wide-row sowing the width of the carcass was increased accordingly by the width of the row. The authors assumed that the horizontal roots of seedlings

spread in the space between the rows over an area of 20 sq cm at the most.

The monolith with the roots was removed in the following manner. The metal hood was placed on the site of excavation across the row and slightly pressed into the soil to mark the borders of the monolith. The earth was removed from both sides of the row along the borders with a spade to the entire depth of root penetration (in the Moscow Region during vegetation the root system grows down to a depth of 20 cm in May, 25 to 30 cm in June-July, and 40 to 50 cm in August-September). Then narrow slits were made with a spade across the row, and also along the borders marked. As a result, a rectangular lump of soil (a monolith) of the corresponding size containing seedlings was formed, and a metal box placed over it and pressed down to the required depth. Then the monolith was undercut with a metal bar inserted into the bottom opening of the box, lifted by the handles, and taken to the place of washing.

Before washing the whole root system the monolith was pierced with metal rods to preserve the natural arrangement of the roots. To study root penetration in the horizons the monolith was cut at intervals of 5 cm through slits in the sides of the hood and each layer was washed separately. The washing was done on a sieve with 0.3-mm openings, and thus small roots broken off during the procedure were retained. Experience showed, however, that such roots were few in number because apple-tree roots are quite vigorous.

Excavation of the monolith and washing of the root systems took one-and-a-half to two hours. Since five to eight plants were washed at the same time, 15 to 20 minutes was spent on each plant.

In the first half of the vegetation period these procedures can be done by one person, but in the second half two persons are needed because the monolith weight increases. The next monoliths with the root system are taken 1 to 2 m away from the site of the previous experiment, which does not cause any changes in the water-air conditions of the growth of the remaining seedlings. The simplified technique described undoubtedly deserves attention, especially when a great number of plants have to be studied.

We mostly used the method of washing for studying the root system from spring to autumn and in the spring of the following year. First we measured the length of the main

root, and then the lengths of the roots of the first, second, third, and subsequent orders branching from it. As a result we found the total number and length of the roots of the whole system.

It was found that during the first year the length of most (about 99 per cent) of the roots of seedlings of fruit and forest varieties ranged from fractions of a millimetre to 8 or 10 cm. Up to 65 per cent of roots of apple seedlings had a length of 1 to 5 mm. A seedling, particularly that of an apple tree, had very many roots in late summer and in autumn, and therefore it was extremely difficult to measure even a single root system with a ruler. To be able to measure a great number of root systems the procedure had to be simplified: the length of all roots, from hardly visible ones to those 8 to 9 mm long, which constituted the bulk of the roots, was determined by eye without measuring them. Control measurements showed that this skill could be acquired easily and quickly. Roots 9 mm to 8 cm long were measured with a plate proposed by us, and those longer than 8 cm (fractions of one per cent), with a ruler.

In spite of the simplification, measurement of the root system is still an extremely lengthy and tiresome procedure. For instance it took 77 hours to measure 38,500 roots of a wild apple seedling in the autumn. Though the root systems of seedlings of other fruit plants (pear, sour cherry, and others) have considerably fewer roots, it is extremely hard to determine their length and amount. This induced us to find the following, much easier, method.

As a result of measuring the roots (a total of 350,000) of over one hundred seedlings of different varieties, which took 700 hours, a very easy way for recording the length of the root systems of one-year-old seedlings of fruit and forest varieties was found. It was established that the average root length of one and the same botanical species, and of all its parts, i.e. all individual fibrous nets, remained fairly constant during the whole vegetative period, which was explained above and is illustrated in Table 42, p. 183. For example, the average root length of the entire root system of a Siberian apple seedling and of its parts was 6 mm. So, instead of spending many hours in measuring the root system, we took only a part of it (50 to 100 roots) and determined its length within an hour. The number of roots in the whole root system can be counted in 1 or 2 hours, and

by multiplying the average length by this number the length of the seedling roots can be determined rather accurately. The whole procedure will take 2 or 3 hours (instead of 77). Owing to this simplification we could, in our further research, take several seedlings at a time and determine the average length of their roots. We were also able to determine root shedding during the vegetative period by this technique.

The washed-out seedling root system, brought to the laboratory in a jar of water, must be measured immediately because the roots change colour if kept for a long time. The root system is measured from the base of its stem; for this a root of the first order is broken off together with the root net. The length of all roots shorter than 8 to 9 mm should be determined by eye, and that of roots ranging between 8-9 mm and 8 cm, with a plate graduated on the side (1 to 5 cm) and the right bottom edge (1 to 8 cm). All the divisions are subdivided into millimetres. We believe that a plate (plastic or metal) of this size is most convenient for this work.

A moistened white cloth is placed on a piece of glass 20-30 sq cm in size, and the broken off root net is put on it and covered with a similar cloth, then moistened with water, whereupon the upper cloth is uncovered little by little and the roots are measured. After one net has been measured the next one is taken, and so on.

According to recent data published by Shalyt and Zhivotenko (1968), of the numerous methods suggested for washing root systems in estimating the mass of underground organs, wide use was made of the manual method employing a home-made machine described by Shalyt (1968). The soil sample was placed on the upper sieve with 2×2 mm mesh and washed with water. The washed-off soil dropped onto the lower, finer sieve, entraining the smaller roots, the larger ones remaining on the top sieve. Since considerable amounts of sand and slime passed onto the lower sieve and stopped up its openings, the contents had to be thoroughly stirred several times and the sieve rinsed with water.

Mechanized methods of root system washing have been described in the literature recently. One of such devices is the Soviet root washing machine УОК-50 described by Stankov (1951). Its construction is simple: a soil sample is put into a bunker and moved by a controlled worm con-

veyer onto a pan, where part of the soil is washed off with a water jet; then the roots with soil particles sticking to them fall on a swinging sieve fitted into a bath, where they are washed clean. Some defects, revealed in testing the machine, were corrected by Shalyt, Zhivotenko, and Serkova by adding a few devices.

1. The soil samples were previously soaked in water and placed directly onto the top pan, bypassing the bunker with the worm conveyer. But if the conveyer was switched on, the exit opening of the bunker was covered with a specially made oilcloth sleeve to prevent the small roots from being blown away.

2. Since the pan intended for the first sifting had large meshes (2×2 mm), some of the small roots were lost together with the discarded water. To prevent this the authors soldered a brass net with 0.25×0.25 mm mesh over the pan.

3. The water drained from the bath contained many short pieces of thin roots less than 0.5 mm in diameter. Therefore two troughs with pans were placed at the bath outlet, one under the other, so that the slime would settle on the bottom, while the floating roots would move by gravity onto a very fine sieve under the lowest trough. This minimized the loss of small roots during washing.

To establish the reliability of comparison of the results of the two washing methods described, a series of samples were drawn, each sample being divided into two equal parts, one of them washed on the YOK-50 machine and the other on the manually operated machine. It was found that the time needed for washing by the manual method was almost twice that needed for washing on the YOK-50 machine, but the quantitative results were comparable.

Shalyt and Zhivotenko (1968) showed that the litter was considerable (452.4 to 1,144 g per 1 sq m) and had to be taken into account when estimating the phytomass. They believed this to be of radical importance since there was no reliable method of distinguishing the living roots from the dead ones in the underground part of the phytocoenosis. That is why the litter had to be considered.

Treatment of Data

The information gained was recorded on graph paper, the branching orders indicated by figures (Table 33).

Table 33

Record of Root Length in Individual Branching Orders

Roots	Branching orders, length (mm)				
	2nd	3rd	4th	5th	etc.
Main 25.4 cm First order 15.7 cm	12	3			
	and so on				

Individual parts of the root system or the whole system can be drawn on a plan or photographed in the course of washing, and samples can be drawn. After washing, the root system is taken to the laboratory, where the length and amount of roots are estimated and the absorbing surface area determined (this is described further in the section dealing with the adsorption method).

Table 34

Results of Measurement of Above-Ground Part and Root System of Apple Tree Seedlings

Characteristics	25.V	9.VI	6.VII	10.VIII	14.IX
Height of seedling, cm	5.7	7.9	14.0	29.5	42.5
Depth of root penetration, cm	15.0	23.0	23.5	45.0	45.0
Zero order, cm	15.0	16.8	38.5	20.5*	45.5
First order:					
cm	59.2	235.0	408.5	460.6	760.6
number	42	89	118	95	190
(and so on, up to the seventh order)					
Length of entire root system, cm	83.8	648.2	1,886.4	8,384.1	16,289.9
Number of roots in it	116	906	2,726	12,142	26,094
Average root length, mm	7	7	7	7	6.2

* The end of the tap root had died off.

The results of root measurement and recording of the whole root system are tabulated (Tables 34 to 38).

Abdullayev (1966) recorded the results of estimation of a mulberry root system as follows (Table 38).

Table 35

Characteristics of Roots of Apple Tree Seedlings According to Length and Branching Orders

Grades of root length, mm	Number of roots of given length							Total	
	Zero order	1st order	2nd order	3rd order	4th order	5th order	6th order	Number	%
1-5	—	6	715	4,153	2,557	470	6	7,907	65.1
6-10	—	14	282	1,233	680	64	—	2,273	18.7
11-15	—	10	204	403	190	—	—	807	6.7
16-20	—	7	138	118	60	—	—	323	2.7
21-25	—	8	142	82	22	—	—	254	2.1
26-30	—	5	93	30	5	—	—	133	1.0
31-35	—	7	66	31	1	—	—	105	0.8
36-40	—	—	44	19	—	—	—	63	0.6
41-45	1	2	37	20	—	—	—	60	0.5
46-50	—	4	29	14	1	—	—	48	0.4
51-400	—	32	96	41	—	—	—	169	1.4
Total	1	95	1,846	6,144	3,516	534	6	12,142	100.0

Table 36

Apple Seedling Roots of Various Interbranching Orders, %

Root order	Washing time				
	May	June	July	August	September
Zero	0.9	0.1	0.04	0.01	0.01
First	36.2	9.8	2.56	0.8	0.7
Second	62.9	65.1	26.4	15.2	10.9
Third	—	24.3	54.6	50.54	38.77
Fourth	—	0.7	15.6	29.0	37.4
Fifth	—	—	0.8	4.4	10.3
Sixth	—	—	—	0.05	0.9
Seventh	—	—	—	—	0.02

Table 37

Average Root Length in Various Branching Orders of Apple Tree Seedlings, mm

Root order	Washing time				
	May	June	July	August	September
Second	18	25	35	48	40
Third	3	5	8	16	12
Fourth	—	2	3	6	7
Fifth	—	1	1	4	4
Sixth	—	—	1	2	2
Seventh	—	—	—	2	2
Eighth	—	—	—	—	1

Table 38

Root Growth of Mulberry Seedling

Characteristics	Date of excavation						
	16.V	16.VI	16. VII	16.VIII	16.IX	16.X	16.XI
Sum total of roots, m	0.04±0.002	1.1±0.03	7±0.2	13±0.3	18±0.4	20±0.4	21.5±0.3
Weight of roots, g	0.1	0.6	2.0	5.5	13.5	19.0	19.8
Depth of penetration, cm	4	12	43	56	74	85	86
Branching radius, cm	2	8	16	27	36	39	39

Evaluation of the Method and Its Applications

The method of washing is the principal technique employed for studying the root system of seedlings and young fruit and forest plants, its structure, activity, and distribution in the soil. It can also be used as an auxiliary to other methods. This method also ensures efficient evaluation of the qualitative and quantitative changes in the soil under the effect of various agrotechnical measures (fertilizing, irrigation, top-dressing, etc.).

CHAPTER 7

FIELD (GLASS-PANEL) METHOD

Specific Features and Purpose

The field (glass-panel) method consists in observation of root growth through glass panels placed against the soil. Sachs (1865) was one of the first to suggest the technique. Later on it was further elaborated and used for observation of the roots of herbaceous plants and then of woody plants (fruit plants included) by many researchers: McDougal (1900), Rotmistrov (1913), Vorobyev (1916), Modestov (1915), Kroemer (1918), Kachinsky (1925), Harris (1926), Kinman (1933), Rogers (1932), Dragavtsev (1936), Gushchin (1941), and others.

Sachs (1865) studied the root system of plants by observing it directly in natural conditions through glass panels placed in a horizontal, inclined, or vertical position against any root in the soil. McDougal (1900, 1916) observed the growth of roots of woody stocks through glass panels (in the zone of root movement) at intervals of 7 to 15 days during the whole vegetative period. He placed the panels on the soil surface so as to have a good view of the roots on the horizontal and vertical trench walls and of the vertical roots (in the latter case he placed the panels 60 cm below the soil surface). The panels were layed close against the soil leaving no space in between, and were shaded.

Rotmistrov (1907) believed that objective information on a root system could be gained only by observing it during the entire vegetative period, asserting that data recorded at the time of examination alone was insufficient. He widely used the glass-panel method in his studies of herbaceous plants.

Vorobyev (1916) built a small root cabin 2 m high with 1×1.5 m glass panels on the Volsky experimental plot. The pillars had longitudinal slits. He found it difficult to observe the root hairs and maintained that the method

had essential shortcomings since only part of the root system was visible, while the remaining roots extended beyond the panel.

Modestov (1915) built root cabins on the experimental plot of the Timiryazev Academy, which were completely hidden in the ground (like tiny dungeons). The plants were planted parallel to the cabin wall, and observations were made from the house through a glass-panelled trench wall. He also grew flax in boxes with glass walls inclined at different angles; thus he could observe the root system during the whole vegetative period.

Kroemer (1918) constructed root cabins for observing the root system of grapes. The cabin consisted of five boxes for growing plants. They were 1.5 m high and 1.2 m wide placed in a row 80 cm above the ground. The front of each box, which was made of thick glass, had a slant of 10° and faced the cabin. The bottom and sides were concrete, while the top was made of wood, which enabled the soil in the box to be changed when required. The glass walls of the boxes faced a dark passage in which electric lamps covered with yellowish-red glass were burning during observation. In Kroemer's opinion, the serious drawback of the glass-panel method was that the roots extended beyond the observer's field of vision, which considerably reduced the value of such cabins.

Harris (1926) used simpler constructions—glass boxes and frames placed at various depths and distances from the trunk, depending on the depth of the downward spread of the roots under study.

Root Cabins and Root Laboratories

Ever since 1932 Rogers has been using special cabins for studying the root systems of fruit plants. In recent years he has been conducting his observations in a large underground laboratory. At the very beginning of his research he came to the conclusion that boxes with glass panels considerably limited observation of the roots and abandoned them in favour of trenches. At first he dug four observation trenches in the orchard at the East Malling Research Station (Kent, England), but later built an underground laboratory (root cabin). The first observations were aimed

at studying the soil conditions, particularly the effect of soil humidity on the growth of the root system. The laboratories were built as follows.

A trench was dug and wooden cabins sunk into the soil. One side of the cabins was of plate glass 6.2 mm thick and faced the soil. The cabins were arranged tangentially to a circle with the tree trunk in the centre, at a distance of 75 cm from the trunk. The cabin windows were firmly supported against the soil with strong steel frames and spring presses.

In Rogers' opinion, a vertical (or near-vertical) position of the windows was evidently the main reason for his success because minute soil particles did not accumulate on the glass surface, obstructing the view, as with a sloping glass. The cabins were 2.25 m long, 1.2 m wide, and 1.35 m high. The trench had steps at one end for easier entry into the cabin. The roof of the cabin was made of two hinged halves fitted with skylights and could be thrown open. The glass surface (1.1 m high and 0.8 m wide) was divided into six sections, each with its own light-proof wooden shutter. Since some free space usually remained between the glass and the soil against which it was placed, the soil lying close to the glass was first removed in layers corresponding to the genetic horizons, then dried, repacked tightly in the correct order and compacted with a wooden strip. It was important that the soil had an accurate profile and was in good contact with the glass.

Each window was divided into 1.3-cm squares by a steel wire net embedded in the glass. The rows and columns of squares were numbered. In some cases the squares were notched with a writing diamond point on both sides of the glass to avoid parallax. Owing to the squares every new root growth could be drawn accurately on a map.

All the windows faced north to prevent direct sun rays from falling on the root. Observations were made in daylight within the shortest time possible. Rogers discarded the objection that it was unnatural for roots to grow against a sheet of glass, arguing that the surface of a glass panel is similar to that of a smooth grain of sand or silica rock.

According to some authors, the drawbacks of this technique are the limited visibility of the root samples and their exposure to light during observations. An advantage of the glass-panel method is the possibility of observing the same

roots for a long period of time under conditions close to natural.

Rogers and Head (1968) built a new laboratory at the East Malling Research Station in 1960-1961. The adopted arrangement greatly facilitated the examination of absorbing roots. The first stage of their research included a series of observations of the root growth of apple trees, plum trees, and black currant shrubs.

Almost the whole reinforced-concrete structure lies below the soil surface (Fig. 47). Its internal length is 29.3 m, width 2.13 m, and height almost 2.13 m. Forty-eight observation glass panels are fitted against the soil on both walls of the laboratory (Fig. 48).

The laboratory was constructed in a long trench 2.13 m wide dug out by a power shovel. The trench walls were carefully braced with boards to keep the natural genetic soil horizons undisturbed. No traffic was allowed near the trench while the laboratory was being built.

The main framework consisted of interlocking concrete pillars and lintels and the roof was cast in situ on curved

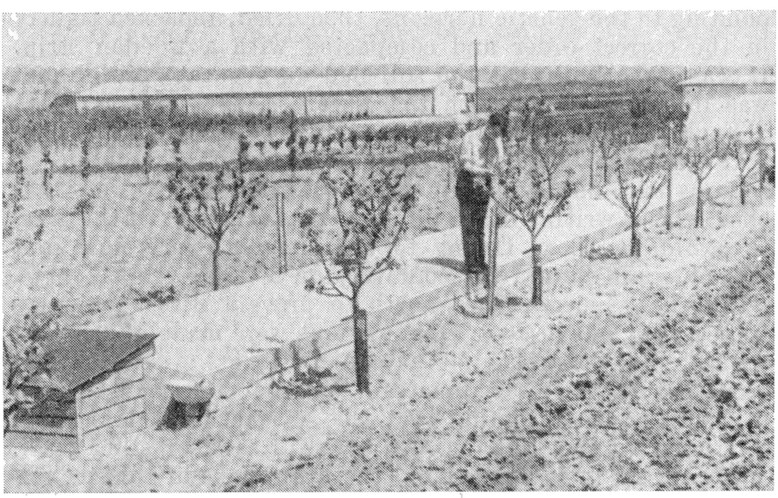


Fig. 47. Exterior view of the root observation laboratory at East Malling Research Station (4-year-old apple trees) (after Rogers and Head)

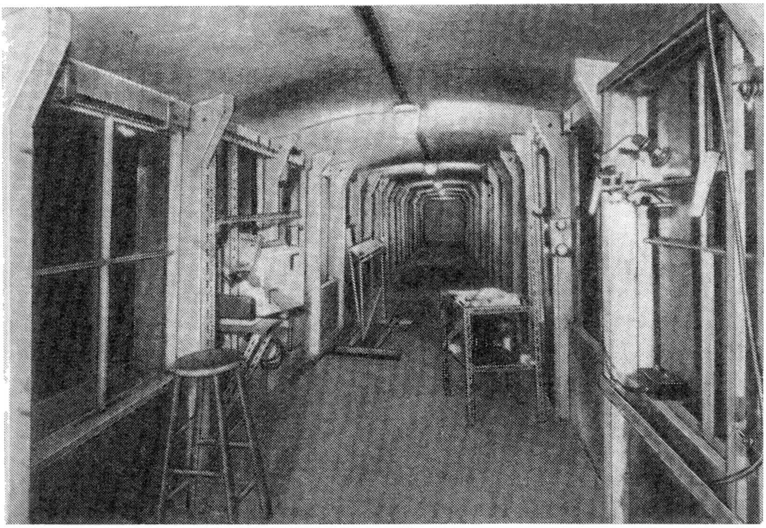


Fig. 48. Interior of the root laboratory with observation windows on both sides (after Rogers and Head)

expanded metal reinforcement. The windows between the pillars were supported on concrete walls and fixed firmly at the top by adjustable steel clamps. Some of the principal features of the construction are shown on Fig. 49.

The window frames were 1.22 m long and 1.07 m wide. The glass panels were 6.3 mm thick with engraved 1.27-cm squares for locating roots and recording them on the plan. Most windows were divided into four panels, but six were divided into 20 individually detachable panels through which samples could be drawn. Before the frames with the glass panels were installed a 2- to 4-cm layer of soil behind them was removed; the soil from each genetic horizon was dried separately, and then re-packed tightly in the same order. The window frames had a 2.5-cm forward slope, i.e. their upper parts were inclined away from the plants so as to maintain better contact between the soil and the glass.

If spreading of roots to neighbouring windows was desirable, the spaces between the windows were bridged behind the concrete pillars on the outside of the structure with strips of thick polypropylene. But if interlacing of the

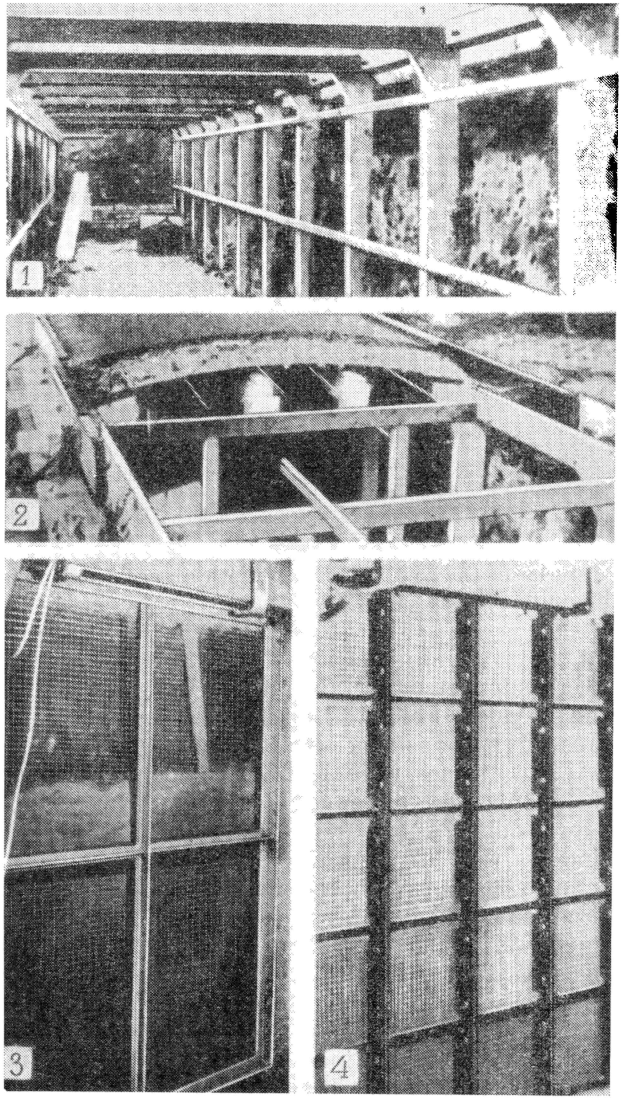


Fig. 49. Certain details inroot laboratory construction:

1—installation of concrete supports for windows; *2*—roof construction; *3*—observation window with four panels; *4*—win dow with 20 panels (after Rogers and Head)

roots of neighbouring trees was undesirable, transverse polypropylene sheets were driven into the soil. All the windows were usually closed with light-proof shutters. To provide normal conditions for observations the laboratory was entered through a light-proof vestibule at ground level. Six small light-trapped ventilators supplied the laboratory with fresh air.

In this laboratory Rogers and Head (1963) were able to make a more detailed study of the root system. Eighteen apple trees, four plum trees, and eight black currant bushes grew along the sides of the root laboratory. Twelve apple trees were four-year-old trees of Worcester Pearmain on Malling-Merton 104. They were planted 3.65 m apart, 67 cm from the observation windows. The younger trees were planted only 30.5 cm away from the glass. In a few years they could be replanted further away. On planting, the roots were not cut very close and were placed so that their ends were a few centimetres from the glass panels.

Modifications of the Method

Kinman (1932, 1933) studied thin roots of peach, plum, and apple trees in California using thick 90 × 90-cm window panes placed tightly against a vertical trench wall 1 m in length, 75 to 90 cm from the trunk. To prevent temperature fluctuations in the trench the panes were covered with shutters and the trench was filled with straw in intervals between observations. Gaps between the glass and soil were filled with clean dry sifted sand and then the glass was fixed to the soil.

Kholodny (1939) pointed out that contact of the root with glass or other chemically neutral bodies, even with rather strong one-sided pressure on the root apex, did not cause any mobile reactions in the zone of elongation.

Dragavtsev (1938), who studied for a number of years the root systems of some fruit species, those of subtropical plants included, under conditions of the Black Sea coast, believed that field laboratories of the type of East Malling would be unsuitable there without considerable modifications. He found that with the glass panels set up in the soil perpendicularly to the direction of the roots studied such a great number of roots gathered at the glass that it was difficult to observe and measure their growth. In his opi-

nion, the glass panels should be fitted in the lateral wall of the laboratory, i.e. radially to the tree.

We recommend not to fix the glass tightly in place, but supply it with special springs, because in the autumn-winter period of abundant moisture the soil swells considerably and even glass panels 5 to 6 mm thick may crack, whereas in the summer the soil shrinks and 1- to 5-mm gaps may form between the glass and soil causing abnormal conditions for root growth.

It was also found that in the winter much water seeped into a cabin built on a flat area and interfered with the observations. So the laboratories had to be moved to sloping ground and side entrances made in them. Even a small slope ensured continuous drainage of excessive water.

To prevent considerable temperature disparities between the laboratory and soil (increase of laboratory temperature in the summer and decrease in the winter) the two doors of the laboratory were padded with heat-insulating material, so that the difference in temperature between the soil and the air in the laboratory did not exceed 1.5°C. The laboratories had only side entrances, therefore the roots were less exposed to light than in the case of trap doors at the top, even covered with shutters.

From 1937 through 1940 Gushchin (1941), working in the Ukraine, dug a trench 24 m long, 1 m wide, and 1.25 m deep and installed glass in 1×1-m frames along both walls. The trees stood 75 cm away from the walls at intervals of 2 m. Observations were conducted every five days, and in the winter every 15 to 20 days; in the middle of each summer month the roots were observed every day for five or six days to establish the daily increment. Fifteen to twenty roots were measured in each plant; the length, diameter, direction of growth, new branchings, and the size of the ageing part were determined. The site of a new root was marked by pasting up a small elongated paper triangle with the date and root length written on it.

Roots of apple trees growing in tubs were also observed through glass panels. The tubs were heated with electricity and cooled with the aid of a refrigerator. The roots of trees planted in glass-panelled boxes were observed systematically in the same manner.

As early as 1948 we studied root growth in the Crimea through unframed glasses, which enabled us to make some

successful observations of root activity in fruit plants. Beginning with 1952 we built at the Timiryazev Academy small underground root cabins 1.2 to 1.4 m in length and height and 1 m in width, and placed them 1 m from the tree trunk. At first we fixed the glass in the frame in a vertical position against the trench, but later sloped it at 7°. The surface area of the glass was 1×0.5 m, its thickness being about 6 mm. Prior to installing the frame with the glass we levelled out the soil, then placed the glass against it, and filled the gaps with soil in layers corresponding to the genetic horizons. There were no essential disparities between the results obtained with vertical and sloping glass panels. The glasses were pressed against the soil with wooden bars in such a manner that they could move a little when required. To reduce the effect of light and summer heat on root growth the top of the cabin was covered with wooden shields, and the glass with a slanting screen of plywood or thick cardboard. The glass panels in the root cabin were not marked with squares.

We also employed observation pits—a simple, inexpensive, and extremely effective method. The pits were sunk under the branch spread, nearer to the periphery. In the podzolic soils of the Moscow Region they were dug 60 to 75 cm deep for studying apple roots, 50 cm deep for pear and 40 cm for sour cherry; pits for observing the roots of plum trees were sunk to a depth of 30 cm and were 50 to 70 cm wide and 40 to 51 cm long. One of the walls with glass panes was placed perpendicularly to the root spread from the trunk. The glass was covered by placing a sheet of plywood or cardboard against it, while the observation pit was closed with a tight-fitting lid made of boards.

Another technique, which proved successful, was digging a pit (semitrench) to a definite depth, setting up a glass against its vertical wall, covering the glass with a piece of plywood of the same size, and refilling the pit with earth. We also employed the method of placing a 30×20-cm glass panel horizontally at a depth of 15 to 25 cm and covering it with plywood and earth. In both cases for observations we removed a small amount of earth, made a record of the differences in root growth, and refilled the pit with earth.

Muromtsev (1940, 1962) observed the growth of absorbing roots for two vegetative seasons in observation laboratories which differed but little in principle from the root

cabins described by Rogers, the main difference being that their roofs could not be opened. In 1956 a small vestibule was added to the laboratory to prevent the inflow of warm air from the outside when the door was opened. The 1939 laboratory model had one observation window of two twin frames and was 65 cm high and 90 cm wide. For convenience of observation the glass was divided into 5-cm squares. The laboratory was installed beside a six-year-old Slavyanka apple tree grafted on wild apple. The space between the root tips and the glass of the observation window was filled with earth sifted through a sieve and repacked according to the soil horizons. The temperature was recorded by thermometers placed horizontally at depths of 15, 30, and 45 cm and at a distance of 35 cm from the casing of the laboratory wall.

Batalov (1952) used special wooden frames with 50×30-cm glass panels. He pointed out that this was much cheaper than constructing root cabins. Instead of one cabin he used ten to fifteen frames.

A disadvantage of the observation trenches, also noted by other researchers, is that the roots grow downwards, beyond the zone of observation.

Budagovsky (1953) studied absorbing roots with the aid of small flat boxes with glass panels fitted on two sides made at the Michurin Fruit and Vegetable Growing Institute. The distance between the parallel glasses was 1 to 1.5 cm. The boxes were filled with soil, leaving an empty space of 5 to 10 cm in the middle; for this purpose a net with 3- to 4-mm mesh was fitted into the sides of the box. The plant studied (dwarfing apple rootstocks in this case) was planted between the glass panels. The roots penetrated the upper soil layer and the soil-free space, and entered the lower layer of the soil. The absorbing roots of the seedling could be seen distinctly in the space between the two layers, and the root hairs of various rootstock could be studied through a microscope or binocular magnifying glass.

In addition, four-chamber boxes were made for ascertaining the possibility of water transfer from one root to another. The chambers were isolated from each other. For easier observation of root growth both sides of each chamber were fitted with glass panels. Only one apple tree was planted in each box (Fig. 50); two chambers were watered normally, while the other two were left without watering. The

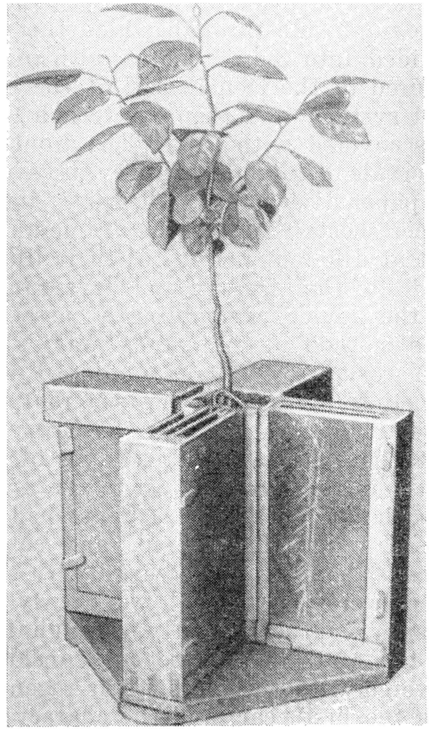


Fig. 50. Four-chamber vessel for studying growth of individual parts of the root system (after Muromtsev)

unwatered soil soon dried off. To illustrate this, the humidity in the watered sections was 30.29 per cent, while that in the unwatered sections was 9.45 per cent. Budagovsky found (with three-fold replication of the experiment) that the water can penetrate from the watered section into the unwatered one via the roots and that a fruit plant must be regarded as a single organism all parts of which are interrelated.

Ussov (1959) dug a trench beyond the branch spread periphery of a peach tree and other stone-fruit plants, located the root net with the aid of a knife, washed out the roots with water, and placed them in a 'cassette' between two glass panels. The device comprised two glass panels (30 × ×35 cm) placed parallel to each other and joined by wooden

planks. The space between the panels was filled with soil. The front side through which the roots were observed was divided into 3-cm squares with oil paint. The device was secured to the trench wall at the site of exit of this small root system, and then the trench together with the device was covered with earth. The front glass was unearthed at intervals of fifteen to twenty days and the roots were drawn on paper divided, like the glass, into squares. A set of such paper sheets with records of one and the same area of roots but at different periods of their life, characterized the dynamics of their growth and development. Owing to the shape of the device, resembling a cassette used in photography, this method of root study was called the *cassette method.*

Yaroslavtsev (1957) employed observation glass panels for studying the growth of the root system of fruit and forest trees in Turkmenia and the Crimea. First he removed the litter (in the forest) or a layer of soil (in the orchard), or both (in the forest) down to the upper horizon of root distribution. Sometimes the roots had to be cut, or those exposed were left in place and covered with a 30×30-cm glass. The glass was covered with earth and litter. Observations were made once a week early in the morning or in the evening, either directly through the glass or without it. If the roots had to be cut considerably before they were covered with the glass, their regeneration was studied during the first year, and the character of their growth during the second year.

In his report to the International Symposium held in 1968 in Moscow Rogers described certain improvements in underground root observation laboratories. For instance, panels of plate glass 6.4 mm thick are supported against the soil by frames of angle-iron 122 cm high and 101 cm wide. Some of the glass panels in several panels of the first laboratory and in all panels of the second may be removed to provide access to the soil or roots (Fig. 51) so that samples can be taken or local treatment applied.

A sheet of transparent polyester film 0.07 mm thick is put behind the removable glass panels owing to which the glass can be removed without disturbing the soil. Small holes or slits can be made in the polyester film, if required. All the panels are marked with a 12.7-mm grid on the soil side of the glass or on the film; it is used as a reference grid and for measuring the length of the roots studied.

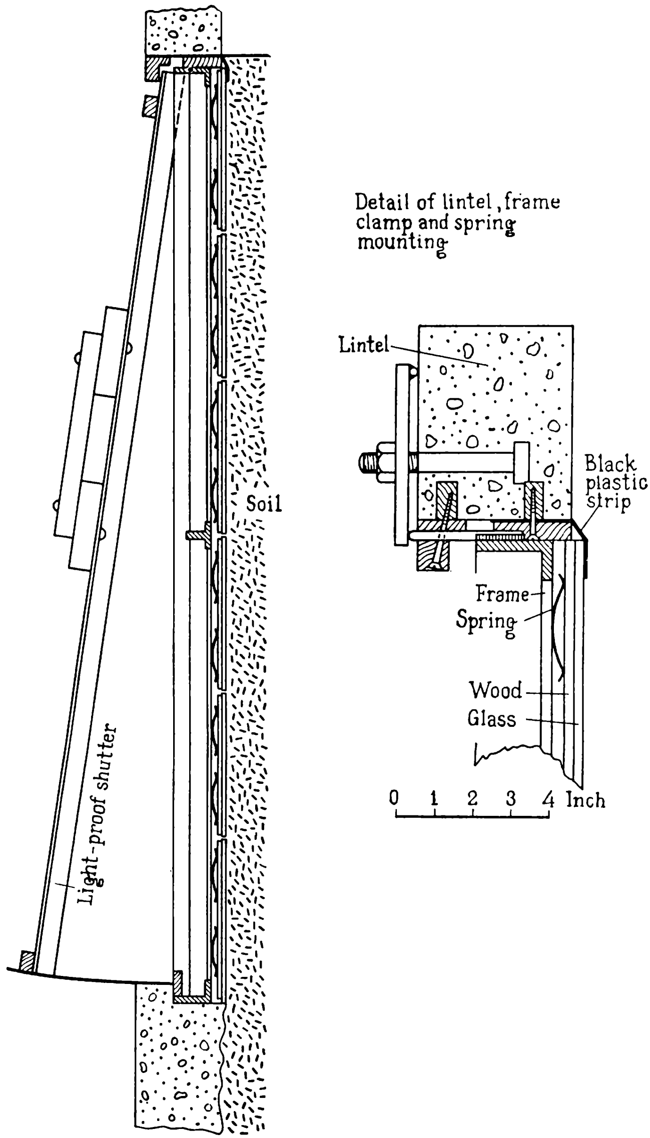


Fig. 51. Mounting of windows (after Rogers and Head)

To study the root system of forest trees Ovington and Murray (1968) installed the observation windows in an underground laboratory in a somewhat different manner. Usually, when root growth is observed through observation windows, a large pit is excavated, the windows are installed in an observation chamber, and the soil is replaced on the side of the windows opposite to the chamber. Then trees are planted in the soil and with time their roots reach the window and can be observed through the observation chamber.

This technique can be criticized because the roots grow under artificial soil conditions (the soil cannot be restored completely to its previous state). It is most applicable for studying fruit plants planted at considerable distances one from another but is difficult to employ in conditions of closed forest vegetation. Planting large forest trees is too expensive, besides, the roots of trees in forest stands come in contact with a great number of root endings so an individually planted tree grows under different circumstances.

The relatively homogeneous soil of Holme Fen (England) allowed the authors to install observation windows with minimum soil disturbance in an established woodland.

A rigid frame about 120 cm long made of three rigid bars (boards) held parallel by an upper cross piece was driven vertically into the ground. A pit was dug at one side 15 cm from the frame, all excavated material thrown clear of the pit. A very sharp knife of hardened steel about 120 cm long and 15 cm wide was easily inserted into the peat soil along the three vertical bars, severing roots up to about 2.5 cm in diameter. As the knife was moved downwards the soil on the pit side was removed and a flat vertical soil face over 120 cm wide and 75 cm deep was exposed. Any projection from the soil face was carefully removed with a sharp knife. The pit was enlarged to a length of 150 cm, so that it was slightly larger than the soil face. Wooden braces with a strong timber lining were built on all sides of the pit with the exception of the prepared soil face and the top to prevent the walls collapsing and to provide a firm ground. A rigid aluminium framework for the observation windows fastened against the soil face was also mounted in the timber lining. Two observation windows measuring 60×60 cm were installed side by side so

that their tops were at ground level; they were of a sheet of perspex 1 cm thick. The material was preferred to glass owing to its strength, flexibility, and workability. To provide reference points a rectangular grid was previously drawn on the perspex with a diamond pencil. The sheet of perspex was fitted on the outer side of an aluminium L-shaped angle and fastened by means of a strong water-resistant adhesive, and a strip of rubber lining 0.3 cm thick was placed between the perspex and frame (Fig. 52).

Each window was attached to the outer aluminium frame by several brass bolts fitted on the aluminium window rim and could be easily moved along horizontal grooves in the frame; the system was maintained watertight by a strip

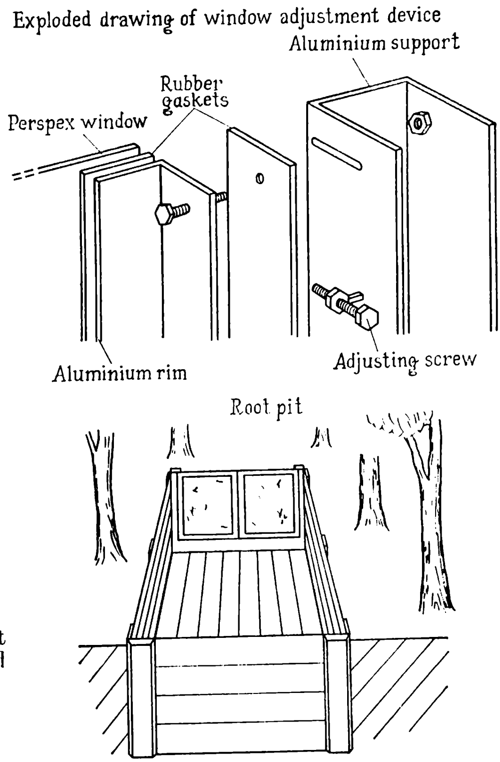


Fig. 52. Details of root pits (after Ovington and Murray)

of rubber lining. The window angles could be varied relative to the soil face by means of a thumb screw attached to the supporting frame and pressing against the surrounding aluminium window rim. In this way a reliable contact between the window and soil face was maintained because the window angle could be easily adjusted if vertical or horizontal shrinkage or swelling of the peat occurred. If air had escaped between the perspex and peat, water would have condensed on the window side facing the soil, interfering with the measurement of the roots and creating still more unusual conditions for them.

Each window was fitted with a shutter to exclude light and to isolate the soil face from changes of air temperature in the observation pit. For protection from rain the pit was covered with a taut sheet of black non-transparent material sloped gently away from the windows. One pit was built in 1962, and the other in 1963, both with two observation windows.

Treatment of Data Obtained

Kinman (1933) recorded new root growth during the vegetative period on the glass using coloured wax pencils. The results of each subsequent observation were marked with a different colour, which made estimation of root length easier. The glass panels were installed on November 25, 1930 in the orchard of a research station in California; root growth started on February 3, 1931 (Table 39).

Table 39

Number and Total Length of Roots

Date of observation, 1931	Myrobalan plum		Peach		Apricot	
	Number of new roots on day of observation	Root length, cm	Number of new roots on day of observation	Root length, cm	Number of new roots on day of observation	Root length, cm
Jan. 15	None	0	None	0	None	0
Feb. 3	42	3.6	7	1.3	None	0
Feb. 17	74	5.1 and so on	13	3.8	1	2.5

Rogers (1932) maintained that the best method for recording certain moments in the life of roots was photography. To overcome poor lighting conditions and reflection he usually placed a black cloth above the camera lens. Though wire grids on the glass panels helped to record the position of the roots, they interfered with microphotography since part of the roots was not visible, and so it was found preferable to take photographs through windows marked with a diamond pencil. New root growth was already observed a few weeks after the glass panels had been mounted. It was possible to record the time new roots appeared, their total amount, and position. Suberized roots and root hairs could be seen and filmed. Records of the environmental conditions (moisture, temperature) were usually made every week. The roots were marked off with coloured pencils which saved much time and was extremely illustrative.

Observations and recordings yield information on the time and vigour of root growth. The following data are recorded during analysis: the time of root growth and the number of roots per year, total root length, maximal growth per day, growth in daytime and at night, etc.

Rogers and Head (1968) elaborated more detailed methods for recording observation results. They made full-scale weekly drawings of new root growth on graph paper (using coloured pencils for indicating the dates) which provided the most comprehensive information on the number, length, and class of root growth and rate of cortex browning. But with a large number of panels, especially with densely rooting species studied, this detailed method was not practical. Various faster methods were tested, for example counting the points of intersection of white roots and grid lines, or counting the number of grid squares containing white roots (Head, 1966). Other methods, including the quickest, visual recording, are still under test.

Detailed descriptions of the typical life history of fruit tree roots are available (Rogers, 1939; Rogers and Head, 1966), and particular aspects have been studied by means of time-lapse films. These films were primarily designed for analysis of rate of growth and other changes over any chosen period. Moreover, if single frames are exposed at intervals of 7.5 to 60 minutes and then the film is projected at a rate of 16 frames per second, the speed of action in-

creases 7,200 to 57,600 times. With such a high speed many interesting features of root development were revealed (shorter intervals are undoubtedly more suitable for detailed study of the soil fauna).

Evaluation of the Method and Its Applications

According to Rogers and Head (1968), though the glass-panel method is suitable for many types of study, as described above, it has definite disadvantages. The glass panels alter the direction of growth of many roots and make them grow in one plane. But in spite of this, the main roots continue to grow at different angles typical of the species, while the various types of roots prove to be normal by comparison with roots carefully washed out from field soil.

The growth of roots on the glass panels was often much more pronounced in the first season than in the years following, which can evidently be attributed both to the initial disturbances in the soil and to the 'wound reaction' of roots cut during transplanting. Beginning with the second year root growth remained rather stable, though its rate dropped somewhat. Valuable results were obtained at the East Malling Research Station from observation through one and the same set of windows over seven consecutive years.

Replication possibilities are usually scanty, therefore it is expedient to repeat the studies for several years; only considerable differences in seasonal cycles can be easily detected, but the time of major changes in root behaviour can be determined accurately.

The possible effect of the glass panels on soil conditions should also be borne in mind. Temperature fluctuations at the glass surface can be greater than in the soil in an open field, but at East Malling, even without special insulation of the roof, the average weekly soil temperatures at the glass and one metre away from it usually differed by less than 1 °C. The conditions of gas exchange may differ somewhat from those in undisturbed soil, but Glover (1967 and private communication), when measuring the soil atmosphere in a similar root laboratory in South Africa, found that the concentrations of oxygen and carbon dioxide near the glass and at a distance of two metres were similar.

The possible effect of light on root growth must also be taken into account. It is very important to shorten exposure to light and provide adequate darkening. It was found that light produced but an insignificant effect on apple roots (Rogers, 1939), but prolonged exposure apparently reduced branching of sour-cherry roots.

It is worth dwelling once more on certain special features of the East Malling observation laboratories. The near-vertical position of the panels proved to be of great advantage because it relieved the glass of most of the soil weight and therefore a glass 6.4 mm thick was sufficiently strong. Even so, cracks formed in some of the large panels, but not in the small (25 $\times$20 cm) ones.

In Root Laboratory 2, special-shape steel springs 17.5 mm wide and 0.3 mm thick were placed between the glass and the steel frame (Fig. 51) owing to which the glass responded to soil contraction and expansion. Small panels proved particularly useful where densely concentrated roots caused local shrinkage of the soil. Windows made up exclusively of such small panels, which were supported only at the sides (as shown in the left half of Fig. 48) were very suitable for many purposes.

Since detailed studies in the laboratory take a lot of time it is very important to provide a comfortable workplace and good lighting. Convenient arrangements for employing a stereoscopic microscope considerably widen the scope of observations; time-lapse cine photography, including microphotography, revealed details of complex changes on and near the roots which otherwise would have remained unnoticed. Rogers and Head supplemented the originally used modified cine-Kodak Model B 16-mm camera (Jones 1965) by a Vinten scientific camera and intervalometer. To diminish the effect of the light, tungsten lamps have been replaced by electronic flash illumination.

Other root observation laboratories built on similar lines are already used for studies of sugar cane in South Africa (Glover, 1967) and coffee trees in Kenya (Huxley, private communication).

Ovington and Murray (1968) checked regularly whether root growth took place. They recorded root lengths during the period of root growth each week on a sheet of thin perspex fixed to the window, tracing the roots with a very fine brush and a quick-drying paint. The tracings were then

copied out on paper and the length of each individual root was measured with an opisometer. The roots were photographed through the observation windows. The root tracings require careful interpretation. Erroneous estimates may be due to the following: (1) drying-off and shrinking of the peat may cause displacement of a root relative to the reference point on the perspex and give a false impression of the growth, and (2) when a root comes in contact with the perspex at a shallow angle, a part of it behind the growing point may swing about in the field of vision and give an impression of growth away from the root. Sometimes a dense network of thin roots may develop at places and interfere with the measurement of individual roots.

The method of glass panels has many modifications, from installation of glass panels in vertical and horizontal positions, building observation pits with glass on one side, construction of various types of chambers, and setting up simple root cabins with one or several windows, to arranging fully equipped underground laboratories provided with binoculars and microscopes and apparatus for photography and cine-filming. All this ensures the possibility of observing roots in conditions very close to normal, which is an extremely important advantage.

The glass-panel method allows one to study in detail the activity of a root system, the growing and absorbing roots in particular, to gain more insight into such aspects as the formation, growth, and dying-off of roots (through natural and recorded external causes), their branching, change from primary to secondary structure, regeneration of roots injured during soil treatment, the root life span, the relation between root growth and soil temperature and humidity, etc. The clarification of these points will contribute to the understanding of plant life and will help to use the data obtained for solving a number of problems of soil management and plant care and for evaluation of the conditions which determine the growth of absorbing roots during different periods of vegetation and in relation to the rhythm of the growth of the above-ground system and fruit-bearing.

Another important advantage of the method is the fact that though only a part of the root system is seen through the glass, the growth, production of lateral roots, and the dying-off of one and the same set of roots can be observed.

The method is most convenient for comparing the growth of both growing and absorbing roots with the growth of the above-ground system. During the second year of observation roots of several orders, i.e. growing and absorbing ones, are studied by this technique. Unfortunately, most researchers observe root growth through windows only for one year, i.e. their studies yield more information on the regeneration of roots than on the natural growth of growing roots.

The glass-panel method has certain shortcomings too, the main being a limited field of observation, which, in addition, lies in a single plane. Roots may move away from the glass very soon after formation. In the first period after the roots have been cut and the seedlings planted, only axial, but not absorbing roots may extend towards the glass.

If studies are made in root cabins or laboratories in which the window panes are to remain in place for several years, a 2 to 3-cm layer of soil lying parallel to the glass has to be renewed, because an excessive humus layer forms as a result of continuous natural dying-off (self-thinning) of roots, which on the one hand impedes observation of the roots and, on the other, creates rather abnormal conditions for their growth. The procedure is not difficult, however, and must be repeated regularly (each two or three years). If roots are observed through observation pits or glass panels installed simply against the soil, there is no need for such replacement.

In spite of its shortcomings the glass-panel method is extremely valuable for studying many aspects of root system biology. With experience, axial roots, absorbing roots, and their root hairs can be studied separately, obtaining authentic information. The method can also be used as auxiliary to other techniques. Kachinsky (1925) claimed that observation of root systems through glass panels is "extremely valuable", but suitable only in solving definite problems.

CHAPTER 8

FREE-MONOLITH METHOD

Specific Features and Purpose

With this method a monolith or a lump of soil is removed from about the middle or from two to three depths of the bulk of the horizontal root spread, then washed out, and the length of all roots on several nets is measured; a comparison of the total length of absorbing roots with the length of roots of the entire sample shows the activity of the growth of the root system.

The method was elaborated by us and used for the first time in 1940 in the Crimea for studying the causes of defoliation in apple trees (V. A. Kolesnikov, 1947, 1962). With moderate time and labour expenditure it is possible to investigate (using several variants and replications of the experiment) the quantitative and qualitative relation between absorbing, intermediate, and conducting roots. With the aid of this method the rhythm of the growth of the fruit plant root system can be observed systematically.

The free-monolith method can also be used for studying the correlated dynamics of growth of the above-ground and root systems, and in this way helps to better understand the diverse activity of fruit plants and to obtain heavy yields. The Soviet researcher Beideman (1939), who specialized in the study of roots, was justified in his belief that the study of the absorbing part of the root system is the key to solving many important problems of plant-growing. He stressed the necessity for studying the root system of plants by placing them under different soil conditions, and advised the researchers to isolate the absorbing portion with methodical thoroughness in order to reveal the complex relationship between the roots and the environment.

We used the free-monolith method widely in our study of the root system of fruit plants. Ever since 1924 we repeatedly maintained that certain regularities in the growth and dev-

elopment of root systems (appearance of the orders of branching, the constancy of the average root length of similar plant species, root-shedding, etc.) are common not only to fruit species, but also to forest, decorative, and apparently all herbaceous plants (V. A. Kolesnikov, 1924, a and b, 1930, 1966). This evidently promoted the successful utilization of the free-monolith method by sylviculturists, viticulturists, and vegetable growers. Therefore we will expound the theoretical background of the method in more detail.

It was mentioned above (in the chapters dealing with the root system and the method of washing it out) that most roots in all fruit plants of all ages are short, from fractions of a millimetre to 5 mm, and only in rare cases to 10 mm and more. The principal factor underlying the method is the similarity of the average root lengths (root coefficients) and of many other features (number of branching orders, dynamics of root growth and root-shedding) in the whole root system and in its parts. Local regularities manifested, for example, in one or two small parts (nets) convincingly elucidate the general picture of the entire root system of the plant. This greatly facilitates the researcher's work and produces reliable results.

In our early studies (as far back as 1920-1923) at the orchard of the Timiryazev Academy we obtained data on the average root length (root coefficient) for some species and varieties of fruit, forest, and decorative plants, and found that it remained almost the same in each species during the entire first year of life. This is illustrated by Tables 40 and 41 showing the values for apple and pear.

Table 40

Growth and Development of Chinese Apple Root System

Characteristics	25.V	9.VI	6.VII	10.VIII	14.IX
Number of orders of root branching	2	4	5	6	7
Total length of root system, cm	83.8	648.2	1,886.4	8,384.1	16,289.9
Number of roots in system	116	906	2,726	12,142	26,094
Average root length, mm	7.2	7.1	6.9	6.9	6.2

Table 41

Growth and Development of Wild Pear Root System

Characteristics	23.VII		30.VIII
	Plant No. 1	Plant No. 2	Plant No. 1
Number of orders of root branching	5	6	7
Total length of root system, cm	3,464.5	3,175.9	8,897.3
Number of roots in system	3,323	3,146	776
Average root length, mm	10.4	10.1	10.8

Measurements showed that the average root length (root coefficient) ranged between 6.2 and 7.2 mm in Chinese apple, 10.1 and 10.8 mm in pear, 3.6 and 3.7 mm in pine (according to our data and those obtained by Nobbe* in Germany), 7 and 7.6 in spruce and fir (values obtained by Nobbe and Morozov*), and was 10 mm in wild cherry, 8 mm in Vladimirskaya cherry, 14 mm in mahaleb cherry, 8 mm in maple, 10 mm in ash, and 16 mm in Chinese scholar's tree.

From a considerable body of data obtained as a result of recording a vast number of root systems of various plants we found that branching and the average root length in all parts of the root system, even in small fibrous nets, were in conformity with the general pattern, that is, even a small part of the root system replicated the entire root system in many respects. Anyone can verify this by examining the root system of any fruit plant seedling.

Table 42 shows the results of an analysis of the branching orders and average root length of the whole root system and of its parts in Siberian apple, made in July, 1922. At that time the apple seedling had 6,366 roots with a total length of 37.62 m. The average root length in the whole system (root coefficient) was 6 mm. The plant had a

* Only the lengths of the seedling root systems and the number of roots were quoted in Nobbe's (1875) and Morozov's (1914) works; we obtained average root lengths, which proved to be very close to our own findings.

Table 42

Analysis of the Root System of an Apple Seedling (Timiryazev Agricultural Academy, Moscow, July 13, 1922)

No. of root net	Order of branching					Total	Average root length, mm
	0	I	II	III	IV		
0	26.8/1	—	—	—	—	26.8/1	—
1	—	16.3/15	16.2/50	1.3/8	—	33.8/73	5
2	—	13.5/1	84.5/108	25.3/111	—	123.3/220	6
3	—	66.8/19	249.2/369	37.1/210	0.1/1	353.2/599	6
4	—	7.0/1	32.7/62	3.2/15	—	42.9/78	6
5	—	19.7/2	147.4/149	57.4/224	—	224.5/375	6
6	—	15.5/1	145.9/97	90.2/319	0.1/1	251.7/418	6
7	—	28.8/4	112.5/171	10.0/74	—	151.3/249	6
8	—	12.6/1	120.1/68	147.9/367	5.6/50	286.2/486	6
9	—	13.2/1	94.3/70	65.6/212	0.5/5	173.6/288	6
10	—	11.5/1	92.3/87	33.7/157	—	137.5/245	6
11	—	11.7/1	96.6/76	34.9/147	—	143.2/224	6
12	—	71.4/11	299.2/447	90.9/361	0.6/3	462.1/822	6
13	—	7.8/1	17.7/38	0.6/6	—	26.1/45	6
14	—	9.2/3	26.5/46	1.2/10	—	36.9/59	6
15	—	7.8/1	19.1/41	0.2/2	—	27.1/44	6
16	—	250.0/82	805.3/1,147	205.9/907	0.4/4	1,261.6/2,140	6
Total	26.8/1	562/145	2,359.5/3,026	805.4/3,130	7.3/64	3,761.8/6,366	6

Note. The numerator indicates the root length, cm, the denominator the number of roots.

primary root which had died off at a depth of 26.8 cm, and on which 145 individual roots and tiny root systems had formed.

To show the average length of individual nets of the root system, we recorded all the root systems found along the entire length of the primary root, but for the sake of reducing the size of the table, only some of them were recorded individually (Nos. 2, 4, 6, 8-11, 13, and 15) and the remaining ones, in groups.

We found that the average root length in any rootlet system was strikingly similar or even identical to the average root length in the whole root system of a seedling, even if the rootlet system consisted of only 44, or 45, or 59 roots.

We recorded and analyzed in this manner over 100 seedlings of different fruit and forest species. The root coefficient was more constant in Siberian apple, and varied somewhat wider in Chinese apple and in cultivated apple seedling varieties and in seedlings of other varieties of hybrid origin. But it remained rather constant in all seedlings of one and the same species or variety from spring through autumn both in the whole root system and in its separate parts (rootlet systems).

The root coefficient, easily estimated by measuring a small root net, makes it possible to determine the total root length of the whole system without measuring it, merely by multiplying the root coefficient by the total number of roots in the seedling, which is also recorded very quickly. Even the length of a root system washed out of the soil in the autumn can be determined in three to five hours, whereas the measurement of all the roots would have taken 30 to 40 hours. It has already been said that this simplification enabled us to prove and express quantitatively the phenomenon of self-thinning (root-shedding) of the plant root system, which is of great theoretical and practical importance.

We have established that with age the average length of the root system of a tree reduces, though very slowly. The root coefficient for olive trees aged 3, 10, 150, and 500 years reduced only by 20 per cent. This was confirmed by V.E. Kolesnikov (1953, 1957), who showed that the average root length in a wild apple seedling (grafted on strifling apple rootstock) was 4.71 mm in 1949 (when the plant was 5 years old), but reduced in the years following as the tree reached the fruit-bearing stage: in 1950 it was 4.4 mm, in 1951

3.7 mm, and in 1952 3.55 mm. The average root length was estimated from ten to fifteen observations of three to four trees, i.e. as a result of annual measurements of no less than 4,000 to 5,000 roots.

E. Kolesnikov checked the variation of the root coefficient in apples and found that the average root length for four small fibrous nets obtained by the free-monolith method from four 14-year-old fruit-bearing strifling apples grafted on wild apple rootstock (114 to 137 roots from each tree) ranged between 3.61 and 4.62 mm (Table 43).

Table 43

Root Growth in Strifling Apple on Wild Apple Seedling Rootstock (Moscow Region, Oct. 20, 1952, defoliation had started)

Characteristics	Trees				Average
	No. 1 (Row No. 6)	No. 2 (Row No. 6)	No. 1 (Row No. 7)	No. 2 (Row No. 7)	
Root length, cm:					
conducting	298	225	336	287	—
absorbing:					
intermediate	195	276	157	133	—
active	13	48	34	10	—
Total	506	549	527	430	
Number of roots:					
conducting	16	12	24	40	—
absorbing:					
intermediate	112	90	72	69	—
active	9	31	18	10	—
Total	137	133	114	119	—
Length of absorbing roots per 1 m of fibrous ones, cm	41.2	58.0	36.3	33.3	42.2
Amount of growing roots, %	6.6	23.3	15.8	8.4	13.5
Average root length, cm	3.69	4.13	4.62	3.61	4.01

The marked constancy of the root coefficient allows researchers to check the accuracy of root-net measurements when applying the free-monolith method.

Thus, the free-monolith method is theoretically substantiated by the fact that a part of the root system reflects with sufficient accuracy many regularities in the life activity of the whole root system, namely, the average root length, the growth of absorbing roots and the specific features of their morphology and branching, and their reaction to the environmental conditions.

The theoretical validity of the method was supported by Schitt (1958), who discovered general biological correlations and parallelism in the structure of separate parts of the above-ground system of fruit plants.

Rakhteyenko has long been studying the root system of forest species and the methods of its investigation. In his book *Rost i vzaimodeystviye kornevykh sistem drevesnykh rasteniy* (Growth and Interrelation of the Root Systems of Forest Plants), 1963, he claimed that the free-monolith method was most perfect for studying the growth of active roots, because it was simple, easily applicable, and did not require much effort. In his opinion, a researcher using the method could gain information on the growth of active roots at any time.

Techniques of Root Excavation

First, trees typical of each area examined (average type) are chosen and soil monoliths (samples) with roots removed from them during the entire vegetative period and in the subsequent years. The samples are taken from a depth approximately at the middle of the bulk of the horizontal root spread around the tree, nearer to the periphery of the branch spread. Samples have to be drawn eight or nine times (once a month) in the middle fruit-growing zone and ten to twelve times in the southern areas.

If some special problem is studied by the free-monolith method alone, the depth of the horizontal roots is determined specially in the spring by the easy and quick profile method. A trench is dug close to the branch spread periphery and the depth of root penetration is determined. For example, in the Moscow Region we remove (after checking) soil monoliths with roots from a depth of 20 to 45 cm for

apple, and from 15 to 35 cm, 10 to 30 cm, and 10 to 25 cm for pear, sour cherry, and plum, respectively; in the south the depths are 10 to 20 cm greater.

The free-monolith method was applied for the first time in the Crimea in 1940 to investigate the causes of early defoliation in apple trees in the spring. At first two areas in the orchard were chosen which differed in soil conditions, management, and the state of foliage, and then three typical trees were selected from each. It was found from a previous examination that the main bulk of roots penetrated to a depth of 75 cm.

Samples of root-containing soil were collected every month from April through November from the branch spread periphery, where the main bulk of the fine roots were located. We knew that the diameter of the root system was one-and-a-half times the diameter of the branch spread. The apple trees (Sary Sinap variety on wild apple rootstock) were 35 years old. Small trenches were driven over an area 20×20 cm in size, and monoliths (lumps of soil with roots, to be more exact) were taken from the top 30-cm layer and from depths of 35 to 55 cm and 55 to 75 cm. The monoliths were removed from the sites studied with three replications. A monolith contained 1,109 to 3,522 roots; consequently, with three replications up to 10,506 roots were recorded in a single experimental variant.

The roots were taken from the same peach, cherry, apricot, plum, myrobalan plum, and almond trees in the Crimea, the monoliths being removed clockwise from a half-metre square opposite to the branch spread periphery and from a depth of 40 to 60 cm. Three to five fibrous nets on the average, 10 to 20 cm (sometimes 30 cm) long each, were collected on every excavation, which contained 100 to 300 roots with a total length of 0.5 to 2 m and more. During the whole period of study, 50 to 70 fibrous nets from each tree were examined as a result of twelve to thirteen excavations.

In studying problems such as the influence of the different techniques of soil management, application of fertilizers, and irrigation on the yield of fruit plants we find it advantageous to remove roots from different depths, taking into account the genetic horizons whenever necessary, and preferably in two or three replications. This is easy due to the simplicity of the free-monolith method.

When the roots are unearthed, such features as the colour of the cortex of the conducting, intermediate, and absorbing roots, the character and vigour of branching, the angle at which the roots branch off, the root thickness, and the density of the fibrous root nets must be noted and recorded in the observation journal. We placed the monoliths in jars with water and, shaking them gently, carried them to the laboratory, where they were freed from soil.

At the Pomology Department of the Timiryazev Academy (Kolesnikov, 1954) samples were taken in three to five replications, i.e. from three to five trees of one variety and rootstock. Observations were made every ten to twenty days, depending on the phenological stage, but usually every twenty days. With these intervals it was possible to observe the root system of a tree for three years.

The samples were removed from the periphery of the branch spread, because the main bulk of the absorbing roots was usually found there. A preliminary investigation for determining or checking the location of this zone is advisable. We did not take any samples from the southern quadrant since our observations showed that the soil temperature there was almost one degree higher than that in the other quadrants, while the moisture content was lower.

In further studies we gradually reduced the number of replications and the amount of roots recorded, and we found that in some cases there was no need to remove two or three monoliths from different depths; it was sufficient to take one monolith and record one to three root nets containing 100 to 300 fibrous roots each. Many of our post-graduates obtained convincing results using this simplified technique.

Samtsevich (1951) suggested that the general state of the absorbing roots in an excavated root system be evaluated visually during the entire vegetative period, and the roots recorded as showing good, moderate, or poor growth, or no growth at all. The evaluation is of some importance from the diagnostic viewpoint.

When working with the soddy-podzolic soil of the Moscow Region we took $20 \times 10 \times 10$-cm monoliths from a depth of 15 to 25 cm, while with the chernozem soils of the Lipetsk Region samples had to be removed from a depth of 20 to 40 cm, where the stand thickness of roots was the highest. Soil monoliths may be smaller, but they must contain root nets that can be studied.

The main root was found in the monolith, care was taken not to disturb the soil around it so that the roots did not break off, and then the main root was placed in a jar with water. In this way the roots were adequately preserved.

At the Pomology Department of the Timiryazev Academy (Kulenkamp, 1966) root samples were drawn from 12- to 14-year-old apple trees by the free-monolith method from depths of 15 to 25, 50 to 60, 150 to 160, and 225 to 235 cm at a distance of 150 to 200 cm from the trunk. If there were no roots in the last layer the samples were drawn from a place closer to the tree. A power shovel was used. Analysis of the active growth of vertical roots occurring at various depths simultaneously and in different periods of vegetation showed that the waves of active root growth differed both in time and in depth.

In the spring the vertical roots grew slower than the horizontal ones, because the soil temperature increment reduces with depth. Thus, at the end of May, 1964, the activity of the horizontal roots at a depth of 15 to 20 cm was 17.3 per cent (judged from the length), whereas at a depth of 150 cm it was 12.8 per cent, and in the layer 225 to 327 cm in depth, only 9.2 per cent. By the end of September their activity in the upper layers increased abruptly due to irrigation applied in the first week of the month. In the middle of July the activity of vertical roots at a depth of 225 to 235 cm was twelve to fifteen times that of the horizontal roots.

The vertical roots of an apple tree play an important role in its supply with nutrients and water, especially during droughts and in late autumn, which is evidenced by the high activity of the primary roots at that time, their percentage and duration of activity depending on the moisture content of the soil. We did not observe any summer lulls in root activity.

Specific Features of Roots

It was mentioned above that the fibrous nets are formed of: (a) absorbing, or active, (b) intermediate, (c) conducting, and (d) growing, or axial, roots. It will be recalled that absorbing roots are usually thicker, have a primary bark, and, what is more important, they are white and transparent. The intermediate roots are greyish, sometimes

with an orange tinge, and as thick as the absorbing roots, while the conducting roots are yellow or brown and usually thinner than the absorbing and intermediate ones. The growing roots are much longer and thicker than the absorbing ones as a rule, but are also white and transparent. There are very few of them on the root system and they rarely occur on collected samples; by the law of large numbers their presence in the sample hardly influences the value of the average root length (root coefficient) determined from the total length of all fibrous roots recorded. As early as 1905 Tolsky, and later Ivanov (1953) stated quite correctly that the growing roots are negligible in number and do not play any essential role in absorption.

The absorbing and growing parts of the roots are best detected in fresh material, just removed and washed out, when they are still white and transparent and can be easily recorded. But one has to record the length exclusively of pure white portions of the absorbing roots as the best absorbers of moisture and of substances dissolved in the soil. That is why Ivanov recommended that in doubtful cases a cut be made across the root and then bleached with Javel water and treated with Sudan III to reveal suberization of the exoderm or the presence of suberous tissue, which interferes with absorption. In this way he determined the boundary of the absorbing portion. Absorbing roots of primary structure may be yellowish or darker at the time, but absolutely viable, i.e. capable of absorbing water. In an earlier work Ivanov (1916) established that in a pine absorbing roots that had become absolutely dark were suberized only slightly and could supply the plant with moisture. In the winter months only cells lying on the surface of the growth points are suberized to a considerable extent.

Some American investigators claim that water can enter trees, especially deciduous ones, through roots covered with cork, but only if the roots are submerged in water under conditions inhibiting new root growth (winter colds and summer droughts). It is possible that in such cases water penetrates not through the suberized layers of the absorbing roots, but through the lenticels and cracks at the base of the lateral roots and through injured cortex.

It was established long ago that during growth the plasma spreads evenly inside the meristematic cells, but at rest it separates from the cell walls and forms spherical yellow

bodies. In resting roots the vessels often terminate directly against the meristematic zone because there is no cell elongation zone during rest. In growing roots the vessels form at a considerable distance from the tip of the root. At rest the entire surface of the absorbing and growing roots upwards from the meristem may be covered with epiblema, which is never suberized as a rule and below which lies exoderm undergoing suberization; the degree and nature of suberization differ with the tree species.

The tree species studied were characterized by partial suberization of the exoderm cells, with numerous permeable cells left unsuberized, some of them fitted out with special arrangements for absorbing water from the soil.

Zgurovskaya and Tselniker (1955) found that the primary bark does not die off; it becomes covered with a substance that resembles vagin, but is neither cutin nor suberin, which makes the roots permeable to water. For instance, darkened absorbing roots of oak, ash, and maple can absorb moisture because they contain permeable cells. The authors exercised great caution when identifying the impregnating substance, whereas Rogers and Muromtsev spoke of suberin.

Noskova (1961) studied the anatomy of the absorbing roots of lemon and revealed the presence of permeable cells in the epiblema and groups of a special type of permeable cells lying under it in cells of primary and even secondary origin. The permeable cells ensure the absorption of nutrient solutions and the entry of mycelium of endotrophic mycorrhiza, which activates suberization.

The root cells can endure considerable dehydration when the cell plasma separates from the walls (Ilyin, 1948). As soon as favourable conditions set in such roots start to grow and later give rise to new roots. In his studies of soil moisture Cossman (1939) observed root hairs on the roots of citrus plants and confirmed the presence of permeable cells which facilitate the influx of nutrients and mycorrhizal mycelium.

It was established by Kolosov (1939) that 6 to 7 mm of the root tip (the rootcap and meristem) in pod-bearing plants do not take part in the absorption of nutrients.

The entry of nutrients into the roots and their further advance along the vessels to the stem starts from the cell elongation (growth) zone, which has no root hairs; in other

words absorption of nutrients by the root system of a fruit plant is possible in the absence of root hairs.

As a result of experiments involving the absorption of methylene blue Kolosov (1939) found that the most active absorbing portion of the root lies closer to the tip and that the absorbing capacity sharply decreases with an increase of the distance from it. This is explained by the decrease of physiological activity along the root length.

According to Muromtsev (1955), the absorbing zone of an apple root begins 1 to 5 mm from its tip, and the faster the root grows, the farther from its tip the root hairs occur. A root of primary structure differs morphologically from a root that has changed to secondary structure in its white colour, greater fragility, and much greater thickness. The main bulk of an apple root of primary origin in the absorption zone consists of primary cortex with its outer coat (endodermis) abundantly covered with root hairs. At some distance (4 to 6 mm) from the tip each epidermis cell produces a root hair. The mass of primary cortex is formed of non-differentiated parenchyma cells characterized by considerable turgor, which makes the primary root extremely fragile.

The dying-off of the root primary cortex is revealed by the suberization of the outer layer of pericycle cells, which usually starts between the fifteenth and the twentieth days in the life of the given portion of the root and ends very soon, within three or four days. At the end of this process the central root cylinder is separated from the primary cortex by a layer of suberized cells, the periderm. The cortical cells, being isolated from the central root cylinder by suberized tissue, are not supplied with products assimilated by the leaves and undergo rapid changes. Their turgor decreases sharply, the coats shrink, and the primary cortex and root hairs become dry. The primary cortex dies off within a very short time, one or two days.

The dead bark soon decomposes, revealing a root of secondary structure absolutely free of root hairs and covered with periderm, which consists of several layers of light-brown suberized cells.

The data presented above, although contradictory, suggest that water and nutrients can enter a plant that has no light-coloured roots. Even in the extreme case of a seedling with no absorbing roots, water can penetrate the plant

Under normal conditions apple roots lying in the top horizons are often devoid of light-coloured growing roots in midsummer, but it would be rash to jump to the conclusion that the plant is not supplied with moisture and nutrients at that time.

In general, the absorptive power of roots must be studied in more detail.

The foregoing supports our suggestion made in 1940 that it is necessary to isolate, on the fibrous nets, the groups of intermediate roots, to be more exact the intermediate portions of the root, and to record their length when analysing the results obtained from studies of the growth of absorbing roots in fruit plants (V. A. Kolesnikov, 1955, a, b).

Modifications of the Method

In our opinion, calculations based on the number of absorbing roots per metre of fibrous roots (Sergeyenko, 1939) can also be used for studying the dynamics of the growth of the root system.

S. S. Rubin (1958) estimated the ratio of the length of small roots to the length of skeletal roots. This gives rise to a problem: how to distinguish the small roots from the skeletal (large) ones.

Orlov (1955) recorded absorbing roots of primary structure together with roots that had a mycelian cap and whose primary cortex had died off, whereas Ivanov (1953) measured only the lighter coloured part of the primary absorbing roots, known as the *absorbing root*. We call the darkened parts of the primary roots *intermediate roots*, and roots that have lost the primary cortex, *conducting roots*. Thus, according to Ivanov, the darkened part of the primary root should not be included in its absorbing portion, while according to Orlov, not only roots of secondary structure, but even dead roots should be recorded as absorbing roots. We refer darkened roots to the group of intermediate roots, which is justified by the nature of our studies.

When using the method of soil blocks, or soil samples, which is recommended in practical instructions, the following roots are distinguished in laboratory processing of roots: (1) conducting roots of secondary structure; (2) thick roots of primary structure (white)—growing roots, and (3) fine white fibres of primary structure—absorbing

roots. This enables the small roots to be divided into two fractions: absorbing and growing roots, which is of little importance, however, since the percentage of the growing roots is very small in comparison with that of the absorbing roots.

With the free-monolith method roots are taken from one and the same plant, but they are always new and reflect the combined effect of two opposite processes (growth and dying off). During vigorous summer growth the roots are very active and die off within a short time; the rate of dying-off may be higher than that of growing, so that the length of absorbing roots will reduce. In the autumn the length of these roots increases and under favourable conditions may exceed the maximal summer length; but this does not mean that root growth in the autumn is more vigorous than in the summer.

Ussov (1959) called the ratio of the number of active roots to the unit of the total length of conducting roots in the fibrous portion "the index of root growth activity", and a set of such indices estimated for root segments collected from one and the same tree at definite intervals during the season, "the activity of root growth".

Sergeyenko (1939) and Kolesnikov (1957) suggested that the results of studies be judged from the length (cm) of absorbing roots per one metre of fibrous roots. The relative expression of this value is the same as "the length of absorbing plus intermediate roots in per cent of the entire fibrous net" (after V. A. Kolesnikov, 1962, a). Other scientists also used the length of the absorbing roots per one metre of fibrous roots in their studies.

Kacharava (1966) recorded the length (cm) of active roots per one metre of fibrous roots and expressed their amount in per cent.

Root Recording and Treatment of Data Obtained

The washed-out roots are placed separately, according to the variants and depth, on a glass covered with a wet cloth or paper (filtering paper is preferable). Root lengths up to 8 or 9 mm are determined by eye or with the aid of a measuring plate. One to three fibrous nets containing no less than 100 to 300 fibrous roots are taken; if there are fewer roots on the chosen nets, another one or two nets are added.

We represented the roots on paper by drawing the fibrous net full-size, tracing the absorbing roots with red, intermediate ones light-blue, and conducting ones black ink. Such a coloured picture of the fibrous nets of all the washed-out groups vividly demonstrates the activity of the root system during the vegetative season and before the next monolith is removed. If no new (white), but only orange (light-blue on the drawing) intermediate roots are found in the net, it means that the root system was active a few days ago.

We record the root length in mm, while roots or their portions shorter than 1 mm are indicated by a symbol (usually a check), and add 1 mm for every two such roots when we determine the total root length. A single root consisting of a conducting, intermediate, and absorbing parts is recorded as 45+20+20 (Table 44 and Fig. 53). A single root consisting of an intermediate and an absorbing parts is denoted by two figures with a plus between them and the last figure in bold type, for example 11+**12**. The length of just an intermediate root is recorded in mm with +0 added, and that of just an absorbing root is also recorded in mm, but in bold type.

Table 44

Primary Record of Roots in Fibrous Net

Order of Roots		
First	Second	Third
45 + 20 + 20	**11** 10 + 12 + **13** 10 + 7 + **11**	**10** 11 + **12**

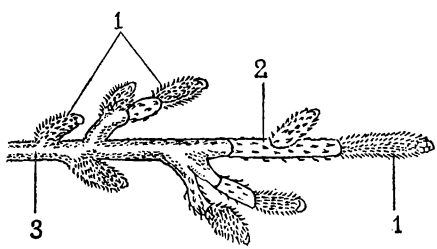


Fig. 53. Branching of fibrous root net:
1—absorbing; *2*—intermediate; *3*—conducting roots

From the primary record the total length and number of roots in the fibrous net can easily be estimated. On adding up the lengths of the roots (Table 44) we find that the total length of conducting roots in the given fibrous net is 65 mm, intermediate 50 mm, and absorbing 77 mm, the total length of all the roots being 192 mm.

With the free-monolith method the total root length of the recorded fibrous nets (one or several) is taken as 100 per cent and the percentage of the length of just absorbing, or sometimes (if necessary) of just intermediate roots or of both at the time of root recording is estimated (Table 45).

E. Kolesnikov (1954) suggested Form 1 (Table 46) for documenting the primary records of roots, and Form 2 (Table 47) for documenting data obtained from analysis of the records.

Table 45

Growth of Apple Tree Roots

No. of tree	Measurements	Roots				Percentage		Length per 1 m of fibrous root	Average root length
		conducting	intermediate	absorbing	total	absorbing	absorbing + intermediate		
1	Length Number etc.								

Table 46 (Form 1)

Roots of Strifling Apple on Wild Apple Seedling Rootstock. Section 1, Row 39, Tree No 4. Depth 20 cm. Eastern Quadrant, May 25 (onset of flowering)

Root 20 mm 5 01 4-2 3-X 0-X 1-3-2	Conducting Intermediate Active	$\frac{25}{1}$ length $\frac{13}{2}$ number $\frac{4}{4}$

Table 47 (Form 2)

Absorbing Roots of Strifling Apple on Wild Apple Rootstock (Biryulevo, Oct. 20, 1952)

Tree No.	Meas-ure-ment	Total	Conduc-ting roots	Absorbing roots				Number of growing roots, %	Average root length, mm
				Inter-medi-ate	Active	Total	%		
			Defoliation has started						
6-2 etc.	Length	5,061	2,981	1,951	13	1,208	41.2		3.69
	Number	137	16	112	9	121		6.6	

In Form 1 the root length is shown in millimetres, roots or parts of roots shorter than 1 mm are denoted by a symbol (× or a check) and 1 mm is added for every two such roots when the total root length is estimated. The length of a conducting root is simply shown by a figure, the length of an intermediate root is underlined, while the length of an active root is preceded by a zero or dash. Sometimes a dash can precede an intermediate root, but in this case the length will be underlined.

In the example given (Form 1) the first root is a conducting root 20 mm long; the remaining six roots are arranged on it. The second root, 5 mm long, is intermediate, so it is underlined. The third, active root is 1 mm long, and a conventional zero (0) is written before it. The last root consists of three parts and the length of each part is shown separately but it is counted as one active root according to its ending. Seven roots are shown in our example, but in practice 80 to 200 roots are measured.

When the free-monolith method is used the total length measured is taken as 100 per cent and the percentage of the absorbing root length (active+intermediate) (Ar) is calculated from the formula:

$$Ar = \frac{l \cdot 100}{L},$$

where l is the length of absorbing roots;

L is the total length of all measured roots.

The principal index characterizing the size of the absorbing surface of the root system is the *length of the absorbing roots.* For comparative study of the state of the absorbing roots in the different years and in different spe-

cies, varieties, and rootstock, their length per year must be estimated.

The vigour of new root growth in the different periods and following the application of agronomical techniques is determined *from the length of growing roots*. Another value employed with this purpose is the amount of growing roots (percentage).

The average root length (root coefficient) shows what kind of roots have been collected—absorbing or growing; with regenerating or growing roots the average length will be much greater.

It is often easier to record the absorbing roots together with the intermediate ones; the curves of their growth are very similar. That is why we employ this method of recording too.

By way of an illustration we present the root recording done by us on two plots in the Crimea in June. On the first plot there was excessive moisture and less favourable physical conditions (Table 48), whereas the conditions on the second plot were better (Table 49).

Table 48

Record of Apple Roots on a Plot with Poorer Conditions, June, 1940
(average for three trees)

Characteristics	Total values	at a depth of		
		0-35 cm	35-55 cm	55-75 cm
Total number of roots	1,556	725	594	234
Total length of roots, mm	19,560	9,219	6,045	3,662
Average root length, mm	12.5	12.7	10.2	13.9
Number of absorbing roots	108	66	33	8
Total length of absorbing roots, mm	325	242	58	26
Average length of absorbing roots, mm	3.0	3.7	1.8	3.2
Relative amount of absorbing roots:				
per cent of total number of roots	6.9	9.1	5.5	3.4
per cent of total length of roots	1.6	2.6	0.5	0.8

Table 49

Record of Apple Roots on Plot With More Favourable Conditions, June, 1940
(average for three trees)

Characteristics	Total values	at a depth of		
		0-35 cm	35-55 cm	55-75 cm
Total number of roots	3,552	2,285	887	319
Total length of roots, mm	46,064	25,555	14,012	6,161
Average root length, mm	13.7	11.1	15.8	19.3
Number of absorbing roots	1,128	915	179	31
Total length of absorbing roots, mm	3,098	2,987	388	85
Average length of absorbing roots, mm	2.7	3.2	2.1	2.7
Relative amount of absorbing roots:				
per cent of total number of roots	31.8	40.0	20.1	9.7
per cent of total length of roots	6.7	11.6	2.7	1.3

In June the state of the roots was much better on the plot with more favourable conditions. On that plot the absorbing roots accounted for 31.8 per cent of the total number of roots and for 6.7 per cent of the total root length, on the other plot the values were only 6.9 and 1.6, respectively. Early defoliation also occurred on the plot with less favourable conditions.

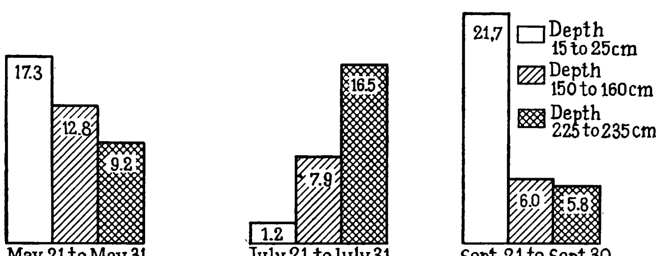


Fig. 54. Changes in the site of the growth zone in apple roots along soil treated by deep ploughing in relation to depth of penetration and period of vegetation (after Kulenkamp)

Table 50

Dynamics of Growth of Absorbing Roots (Per Cent of Total Number of Roots Recorded) During Vegetative Period (after Vu, 1960)

Site of object studied	Date and phenologic phase of above-ground portion										
	bud bursting	onset of leafage and shoot growth	complete leafage	delay of shoot growth	preparation for flowering	mass flowering	onset of fruit ripening	end of ripening	onset of defoliation	end of defoliation	preparation for winter
	IV	V	V	V	VI	VII	VII	VIII	X	X	XI

Note. The romans indicate the months

The dynamics of the growth of absorbing roots can be represented diagrammatically as columns (Fig. 54).

Of interest is the method for tabulating records of the growth of absorbing roots (Vu, 1960; Sivov, 1963) accepted at the Pomology Department of the Timiryazev Academy (Tables 50 and 51).

Table 51

Dynamics of Growth of Absorbing Roots in Saninskaya Chinese Apple with Different Soil Management, mm (after Sivov, 1963)

Sampling time	Bare fallow	Lucerne	Phacelia
1959			
May 28	10.5	10.9	11.9
June 9	17.7	21.4	19.4
June 23	24.6	19.8	36.6
July 20	6.8	5.1	4.2
August 6	20.7	5.0	16.9
	and so on		

For comparative studies of rootlet systems obtained at different periods we expressed the number of absorbing roots on them in our earlier investigations (Ussov, 1959) not in absolute figures, but in relative values, namely, in the number of absorbing roots per 10 cm of total length of the conducting and intermediate roots. We called these values the indices of root growth activity with time (Table 52).

Table 52

Indices of Root Growth Activity

Species	Tree studied	10.I and 20.I	8.VII and 12.VII	7.VIII and 14.VIII	24.IX and 27.IX	22.X and 26.X	20.XI and 25.XI	20.XII and 25.XII
1	2	3	4	5	6	7	8	9
Peach	Aidinovsky	6	5	2	2	5	1	0.5
Mazzard cherry	Zhabule	2	5	3	2	8	7	3
Plum	Reine Claude Wallens	4	1	1	0	1	2	0
		and so on						

Ershov (1957) tabulated the results of his free-monolith studies of the root system of different peach stocks in the Crimea as shown in Table 53.

Table 53

Dynamics of Root Growth in Different Peach Stocks in Non-Irrigated Crimean Steppe (Dzhankoy State Farm) in 1954 (after Ershov, 1957)

Plants and items studied	Number of absorbing roots per 1 m of conducting roots									
Date of observation	25. III	24.IV	23. V	20. VI	15.VII	15.VIII	15.IX	15. X	20.XI	17.XII
Stock:										
peach	0	45	69	97	70	60	136	108	48	53
apricot	0	50	82	108	102	104	172	87	44	37
almond	0	40	41	158	137	67	150	125	76	63
Myrobalan plum	0	67	80	79	111	110	194	144	72	42
Soil temperature at depth of 30 cm, °C	1.5	9.8	15	21.3	24	25.7	21	15	12	6
Soil moisture at depth of 30-40 cm, %	27	24.2	25.2	25	22	22	16	15.2	20	19

Table 54

Absorbing Roots-to-Perished Roots Ratio in Kaliningradskaya Raspberry in Relation to Time of Year

Months	Days	1964		1965	
		absorbing roots, per cent	perished roots, per cent	absorbing roots, per cent	perished roots, per cent
May	21st to 31st	71	29	79	21
June	1st to 10th	77	23	61	39
	11th to 20th	77	23	62	38
	21st to 30th	39	61	89	11
July	1st to 10th	61	39	94	6
	11th to 20th	67	33	87	13
	21st to 31st	65	35	76	24
August	1st to 10th	68	32	92	9
Mean value for season		65.3	34.7	80.0	20.0

Voronchikhina (1966) examined root-shedding in raspberry growing in the orchard of the Timiryazev Academy and found that external factors exerted a considerable effect on the process. The results of her studies are shown in Table 54.

In 1964, which was an unfavourable year with exceptional droughts and heat, root-shedding in raspberry was as high as 61 per cent in some weeks in the summer. Root-shedding in the 1964 season was 34.7 per cent on the average, in 1965 it was less pronounced due to adequate precipitation and equalled 20 per cent on the average, but with a sharp drop in temperature in May it reached 38 to 39 per cent. Consequently, root-shedding increases with deterioration in the conditions of root growth.

Evaluation of the Method and Its Applications

The free-monolith method may be the principal or even the only method used for studies of the morphological and biological features of the fruit plant root system. The experience of many researchers has demonstrated that it can also be applied for the same purposes in investigations of forest and decorative tree species, grapes and vegetable plants.

The free-monolith method can be applied in addition to other methods when studying the reaction of roots to different ways of soil management, fertilizing, irrigation, branch trimming, etc. It can be employed for diagnostic purposes to reveal the state of the root system and the causes of various factors responsible for poor growth and poor fruit-bearing.

As has already been mentioned, Rakhteyenko (1963) believes that the free-monolith method is "most efficient", and in Muromtsev's opinion (1963) it "quickly gives a general idea of the absorbing roots-to-conducting roots ratio, which characterizes the overall activity of the root system".

The free-monolith method is now employed in the USSR, Rumania, Czechoslovakia, and other countries.

CHAPTER 9

BORING METHOD

Specific Features and Purpose

The boring method consists in removing roots from the top soil horizons or from the depth of horizontal root penetration with special augers (similar to the commonly used soil auger) of various diameters, washing out the roots, and recording them. It was first employed by West (1934) in studying the root system of citrus plants, and by Schuster (1936), Dukhanin (1938), and others for investigating the roots of fruit plants.

West determined the amount of citrus roots in different soil horizons in Australia, using an ordinary Veihmeyer auger of 2.5-cm diameter. The removed columns of soil, 10 cm in height, were first placed in vessels with water, then on sieves, where the roots were washed free of the earth with running water. The washed roots were dried, cleaned of bits of earth and other objects clinging to them, and weighed.

Eremeyev (1935) employed an auger to study the condition of the absorbing roots of a fruit plant and to determine their requirements for irrigation. He found that with deficiency of water in the soil the new roots turned red; the abundance of white roots, all other conditions being equal, showed that the soil contained an adequate amount of water.

Schuster (1936) examined the distribution of roots thinner than 2 mm in fruit-bearing apple trees growing in California. He took samples along six radii emanating from the trunk (seven samples for each radius), removing them with a soil auger from a depth of 30 cm at intervals of 30 cm, starting at a distance of 1.2 m from the trunk. Thus he obtained 42 samples from each tree and recorded roots at a distance of 1.2 m from the trunk and farther on. The method was successfully used by Batjer and Sudds (1937) in studying the effect of fertilizers on the growth and yield of apple trees.

Construction of Tool for Root Excavation and Techniques Used

Dukhanin (1938, 1939) elaborated a method for examining the root system of tangerine trees with the aid of an auger, working on the krasnozems of the Batumi District. The main techniques are:

(1) a soil monolith with undisturbed root structure is removed from a definite depth with a 25-cm auger of his own construction. The diameter of the cutting part is 0.5 to 0.8 cm smaller than that of the cylinder itself, and therefore the monolith can readily be withdrawn;

(2) the monolith obtained is placed on a special washing frame and washed with water from a sprayer;

(3) having been washed through a metal net, the roots retain their natural vertical pattern.

According to Dukhanin, the size of the auger and, consequently, the volume of the soil monolith can be increased if the problems studied so require. In 1939 he proposed a rectangular tool for the removal of soil monoliths with roots which made it possible to take soil samples and wash out the roots without any appreciable distortion of the natural root pattern. But the removal of monoliths with a rectangular auger takes more time than with a round one. For instance, in one day two workers obtained as many as 60 samples from a depth of 35 cm with a round instrument and another worker washed out 70 to 80 samples, whereas with a rectangular auger only half as many samples were removed and 10 to 12 washed. The rectangular tool is 20×10 cm in diameter and 50 cm long. A metal net is previously inserted in the auger so as to facilitate the withdrawal of the monolith.

Meyerson (1939) proposed two types of auger for taking soil samples without damaging their structure: one 13 cm in diameter and 30 cm long, and the other 20 to 25 cm in diameter and 40 to 50 cm long. Nadyarny (1939) proposed an auger 15.8 cm in diameter and 20 to 25 cm long, with which he obtained 120 to 140 monoliths of soil with roots from two horizons (the top 20-cm layer and from a depth of 20 to 40 cm) in eight hours. In chernozems, monoliths can be taken from depths up to 80 cm, while in heavy soils it is very difficult to obtain samples even from a depth of 40 cm.

Some authors (Shain and Chekmareva, 1940; Shain , 1948) preferred rectangular augers because their cross-section was 21.5 per cent larger than that of the corresponding round tools. But it must be taken into account that work with the former requires much more effort and, in addition, sometimes the earth has to be removed from its sides while it is being withdrawn to prevent entrainment of the adjacent soil.

When studying the influence of rootstock on root distribution in citrus plants in Florida (the USA), Ford (1954) found augers with a diameter of 25 cm most advantageous because they allowed root systems to be obtained even from a depth of 5.1 m.

Yastrebov (1955) suggested two types of round augers: (1) 15 cm in diameter and 50 cm long, (2) 30 cm in diameter and 60 cm long. The basically new feature in their construction was a vertical slit in the auger wall with clamps at both ends so that the auger could be easily separated from the monolith.

Evaluation of the Method and Its Applications

The boring method is simple, inexpensive, and can be used for solving both theoretical and practical problems of fruit growing. In our opinion it should be used not only in studies of the citrus root system, but also that of all fruit plants. Another of its advantages is that it facilitates the observation of the dynamics of absorbing root growth during the annual cycle under definite soil and climatic conditions or in studies of the effect of agricultural measures (soil management, fertilizing, and irrigation) on the growth and yield of fruit plants.

Budagovsky (1953) also maintained that the boring method can be employed in studies of root distribution in fruit plants.

The method is extremely suitable for determining the condition of the root system of fruit, forest, and herbaceous plants, especially for revealing the causes of unfavourable phenomena in the life of a plant.

Rakhteyenko (1961), using the free-monolith method, obtained monoliths with a specially constructed auger once or twice a week in five replications. He planted 86 experimental plots in different forest stands over a period of 15

Table 55

Characteristics of the Root Systems of 4-Year-Old Cultures of Tree Species Growing on Soddy-Podzolic Loamy Soil (Moscow Region)

Species	Average dry weight of single plant, g					Depth of root penetration, cm	Small roots, per cent of total root mass	Under-ground-to-above-ground weight ratio	Total roots, per cent of total weight of plant
	above-ground portion (trunk with branches and leaves)	roots			total				
		large	small	subtotal					
Spruce	18.8±0.7	4.3	8.4	12.7±0.6	31.5	50	66.1	0.7	40.3
Pine	32.1±1.3	6.3	5.6	11.9±0.5	44.0	60	47.0	0.4	27.3

years, in which he dug 140 trenches and collected 574 soil monoliths. The information obtained was treated by the method of variation statistics and the results recorded as shown in Table 55.

West (1934) established that average values obtained from examination of only six monoliths taken from one and the same genetic horizon gave an accurate enough idea of the amount of roots lying in it. Skeletal roots, which are incapable of absorbing nutrients, were not included in the record of the root mass; they were cut away so that only the small roots were taken into account. In citrus plants, which are devoid of root hairs, only the finest branchings of the lateral roots covered with endotrophic mycorrhiza, whose hyphae performed the function of root hairs, were recognized as active.

In West's experiments the boundaries of lateral root spread were found previously by digging a trench at a definite distance from the trunk and driving it on to the periphery till the end of the horizontal roots was reached. This experimental technique yields good results, though it requires considerable effort and time.

Meyerson (1938), working with augers of his own construction, obtained reliable results from six-fold replications. Dukhanin (1938) proved the authenticity of the information gained from studies of the roots by the auger method. He emphasized that after being washed free of soil the roots could be filmed while still lying on the gauze, then grouped according to the genetic soil horizons, and after their total weight had been recorded and the depth of their penetration measured they could be examined and subjected to chemical analysis. Dukhanin claimed that the boring method has the following advantages: (1) there is no need to dig trenches; (2) replications can be obtained; (3) the work is done quickly (a 1,600-cu cm monolith was obtained in 15 to 20 minutes, while the time needed to wash out a monolith with a hand-operated orchard sprayer ranged between 60 to 90 minutes, depending on the soil tenacity). In 1936 he studied the tangerine root system on the terraced soil of the Batumi District and found that the boring method helped to reveal the root distribution in the terraced area and to plan some cultural measures for those parts of the terraces where the root system developed poorly.

CHAPTER 10

VOLUMETER AND ADSORPTION METHODS

Investigators have given much attention to the elaboration of methods for determining the surface area of the whole root system or of its absorbing portion alone. The main techniques of these methods are: (a) submersion of a root system in a vessel with water and measurement of the volume of the displaced water; (b) estimation of the surface area of the cylinder formed by the roots from measurements of their length and diameter, and (c) adsorption of methylene blue or other dyes. With any method used, especially with the adsorption method, it is extremely important that the roots be washed entirely free of soil and other particles foreign matter).

Methods of Root Washing

Only roots in water cultures are free of soil, whereas roots taken from the earth must be cleaned of soil and other foreign particles, especially because methylene blue can be adsorbed on these particles too and the estimated value of the root surface area will be overstated. Various types of physical and chemical "separators" have been employed for separating soil particles from the roots.

Tikhonova (1955) tested several techniques of root cleaning: (1) mechanical, (2) mechanical with additional washing of dry roots with distilled water or ether, and (3) washing fresh roots in the field. She believed the third method to be most convenient. The content of nutrient substances (potassium and phosphorus) in the roots was not altered on dry cleaning or washing.

Dobrynin (1955) tested a great number of chemical agents and mechanical methods for root cleaning and found washing roots in hydrogen peroxide to be the most rational technique; even the root hairs endured the treatment. The

procedure is as follows. The monolith containing the plant roots is suspended inside a glass vessel that has a sparse metal net fitted in the middle of it which prevents the monolith from falling apart and the roots from breaking. The diameter of the vessel must correspond to that of the monolith and it must be twice or three times the height of the monolith, so that enough space is left for the washed-off particles. The washing lasts from 3 to 24 hours, depending on the mechanical composition and moisture of the soil, size of the monolith, variety and age of the plant, temperature of the solution, and concentration of the hydrogen peroxide. The monoliths are removed in 10-cm or 15-cm cubes, and a three or four per cent hydrogen peroxide solution (at room temperature) is used.

The washing procedure can be speeded up in three ways: by using a rocking device, employing catalysts, or washing the roots in two or four vessels in turn. The latter technique is expedient in successive series of washings (so that the reagent is used up completely). The catalysts are calcium permanganate and potassium permanganate, and the solution is prepared by dissolving 2 to 5 g of the salt in 100 cu cm of tap water. The catalyst must be used carefully because large doses may excessively accelerate the reaction and cause an explosion. To avoid this, at first 1 or 2 cu cm of the catalyst solution is added per 1 litre of solution contained in the vessel with the monolith, and then the dose is increased as required. If the root system has to be filmed, clarification of the solution is accelerated by adding a coagulant—the aluminum salt $Al_2(SO_4)_2$ or the iron salt $FeSO_4$, which clears it in 8 to 48 hours, depending on the mechanical composition of the soil.

The life activity of the plant is not arrested by a weak (about 3- or 4-per cent) aqueous hydrogen peroxide solution used for root washing. This was verified by the author of the method in experiments with oats, clover, and timothy. Plants replanted on soil after their roots had been washed out continued their growth and development. This feature will probably permit replanting a plant after examination of its root system and thus make it possible to study the reciprocal influence of different plants and find more efficient grass mixtures.

To reduce damage to root nets when washing out roots from the heavy clay soil of the Leningrad Region, Batalov

(1958) used 9-per cent acetic acid which dispersed small lumps of soil.

Root Washing with Peyev's Apparatus. Peyev (1952), a Bulgarian investigator, constructed a new apparatus for washing plant roots free of soil, which works on the vibration principle widely used in engineering. It consists of a vibrator-electromagnet (Fig. 55) of no less than 100 watts which is fitted to the washing machine of a basket-sieve or a tank. One end of a 15- to 20-cm pivot is welded to the vibrating plate of the electromagnet, while the other has four 25- to 30-cm rods of thin reinforcing iron branching off from it in four directions so that if their free ends are connected

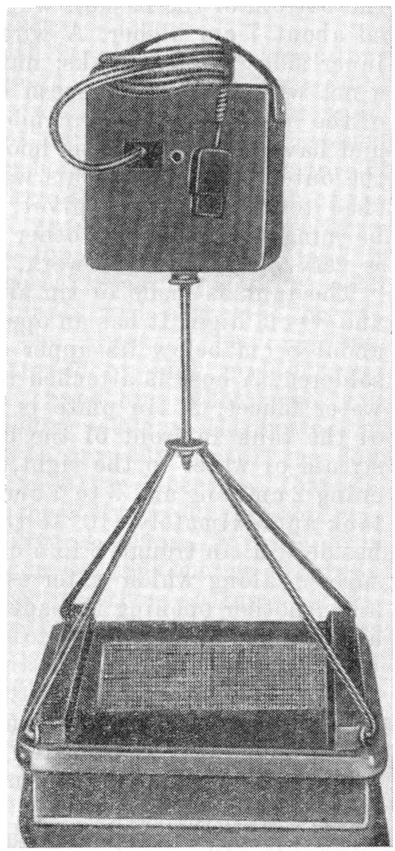


Fig. 55. Vibrator-electromagnet, vibrating pivot with hook and basketsieve

a 25-cm square would be formed. The end of each rod is bent inwards forming a hook.

The basket-sieve is attached securely to the hooks and vibrating pivot. Its dimensions and shape must correspond to those of the monolith to be washed. For instance, a monolith measuring $25 \times 25 \times 10$ cm (the type usually removed for studying the roots of herbaceous plants) needs a $27 \times 27 \times$ $\times 10$-cm basket. The apparatus described here is intended for washing monoliths of this size.

The basket resembles a crate for vegetables. It has wooden legs 12 cm long at its corners and two wooden planks 27 cm long and 1.5×1.0 cm in cross-section at its sides. The lower planks are fastened to the lower end of the legs and form the bottom of the basket, while the upper planks are fastened about 7 cm higher. A wire net is stretched between the inner sides of the planks; numerous tests have shown that a net with 3- to 4-mm mesh is the best. At the top corners of the basket the legs protrude 2 cm above the upper planks and have holes which the hooks of the iron rods enter from the outer side, and in this way the basket is securely attached to the vibrating pivot. Besides, several baskets can be hung one under the other (like vegetable crates), which is very convenient for work.

The tank is made of tin and is 55 to 60 cm in diameter and 30 cm high. It has an opening 1.5 to 2.0 cm in diameter about 5 cm below its upper edge to which a short tube is soldered. A hose is attached to the tube and connected to a water faucet. A tin plate is soldered to the inner surface of the tank in front of the opening so that it diverts the stream of water to the right, along the tank walls. An opening 2 cm long and 3 to 4 cm wide is made at the top of the tank approximately 110° to the left of the first opening, and beside it a tin trough 3 to 4 cm long is soldered to the outer surface, along which water escapes from the tank in a stream. Another opening is made on the same side of the tank about 5 cm from the bottom and a large water faucet is fitted into it. There is still another opening, 3 cm in diameter, in the centre of the bottom; it is stopped with a plug and is opened only for cleaning the tank.

The apparatus is prepared for operation as follows. The vibrator is fastened in a suspended position to a support with a band secured to the top of the electromagnet box. Then the basket-sieve is attached to the vibrator with the

hooks and submerged to a depth of 4 or 5 cm in the water filling a tank set up directly under it. Care must be taken that the basket does not touch the tank walls. The tank must rest on a stand so that the water flowing from the top opening and faucet can be easily removed and it is easier to clean the bottom of the tank from the soil through the central opening after the washing is completed.

The removed monolith is put into the basket carefully, making sure that it does not break into small pieces, which is very important. It is best to do this in the following manner: the basket is slipped over the monolith from the side (that is why the basket is 2 cm longer and wider), then the soil is cut off with a special large flat knife and supported while the basket is turned over.

The basket with the monolith is taken to the laboratory and placed in water (in a trough, barrel, etc.) for several hours so that the soil becomes well soaked. Then the basket is transferred to the tank of the apparatus and fastened to the vibrator pivot with the hooks. The faucet is turned on and the vibrator started. Because of the vibration of the basket with the monolith the water immediately becomes muddy. Escaping through the top opening in the tank it carries away the light admixtures: remains of straw, weed seeds, and dry roots of other plants with a specific gravity less than that of fresh roots. The faucet in the lower side opening of the tank is also turned on and muddy water together with sludge is let out. Sand and other larger soil particles (up to 3 mm in diameter) settle at the bottom of the tank. It is very important to properly control the flow of water into the tank from the water faucet, so that the outflow from all openings, especially from the top one through which the light admixtures escape, is sufficiently strong, but uniform. The water in the tank moves circularly because, flowing under pressure, it strikes against the plate attached in front of the opening on the inner wall of the tank. This helps remove the lighter admixtures. The flow of the water should not be too strong, however, otherwise it may carry away the roots.

The washing usually takes 30 to 60 minutes, depending on the composition of the soil and the amount of roots. A few minutes after the work is begun one should make sure that no rootlets are driven away together with the light particles. If the procedure is followed correctly the root-

lets will neither escape with the water, nor settle at the bottom of the tank. The live roots usually remain suspended in the water inside the basket.

After all soil particles are washed off and only roots suspended in the water and stones lying on the bottom (checked with the fingers) remain in the basket, the muddy water in the tank must be changed or the sample transferred to another tank with clean water. The subsequent washing in the clean water lasts 12 to 20 minutes, the roots being effectively freed from all soil particles. All large particles left on the washed sample are removed with forceps.

The entire process of washing and cleaning is completed within a very short time, in one or two hours, during which the roots remain in the water and keep fresh—this is especially important when their active surface is estimated. The apparatus is simple to operate and no special skill is required. It can easily be built on site.

In experiments including many variants a great number of monoliths have to be washed within a short time. A field laboratory should be set up in such cases, and if it is equipped with ten or twelve apparatuses for washing and two or three for final cleaning of the roots, all work can be done by the conveyer method.

Estimation of the Surface Area of the Root System

Among the first researchers who estimated the root surface area were Levakovsky (1868) and Müntz and Jirard (1891), who determined it by measuring the total length of the roots and their average diameter. Some researchers took into account the weight of the root system, but, according to Krasovskaya (1929), the total root weight cannot be proportional to their absorbing surface, especially because the thickness and structure of the roots vary considerably with the plant.

The weight method can be improved by dividing the roots into absorbing (active) and non-absorbing (inactive) ones according to the root thickness or the presence of root hairs. Krasovskaya (1929) admitted the possibility of such a division in tree species whose roots are more resistant to rupture than those of herbaceous plants. With the use of our free-monolith method the absorbing and non-absorbing portions of roots can easily be distinguished in fruit plants

with absorbing roots ranging between 0.15 and 3 mm in thickness. A study of the absorbing roots (their portions) is undoubtedly the key to solving many important problems of plant growing.

Kolosov (1935) proposed measuring the volume of a root system with a variable-sensitivity volumeter designed by Sabinin and Kolosov. The instrument has the shape of a rather high and wide cylinder into which the root system can be placed undamaged (Fig. 56). As the plant grows, a larger volumeter is used.

A glass tube is soldered to the side of the cylinder, about 2 to 2.5 cm from the bottom and is connected by a short rubber tube with another part of the apparatus—a calibrat-

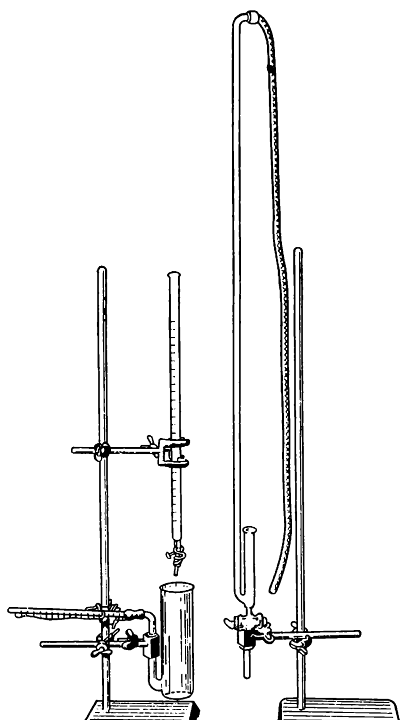


Fig. 56. Volumeters:
The Sabinin-Kolosov model (left) and the Shirshov model (right), accurate to within 0.01 cu cm

ed tube that has an inner diameter of about 2.5 mm. The calibrated tube is clamped in a stand so that it can be adjusted at the required angle to the horizon.

Water is poured into the cylinder until it appears in the calibrated tube. The angle of inclination of the tube depends on the required degree of sensitivity. The smaller the angle, the more precise (but less sensitive) is the apparatus. After the initial position of the meniscus is noted, the root system is lowered into the water; the rise in the level of the water will cause displacement of the meniscus in the calibrated tube communicating with the cylinder. The new position is marked, the root taken out of the cylinder, and water added until the meniscus returns to its initial position. The amount of water added should be equal to the amount of water absorbed by the root system. Then, without changing the tilt of the graduated tube, water is added to the cylinder from a burette until the meniscus reaches the second mark. The volume of water between the two marks will correspond to the volume of the root system measured.

The volumes measured can be determined with the aid of graph paper attached to the calibrated tube. This will greatly expedite the work: it will suffice to note the volume of water added with the meniscus at its highest position and in further measurements to estimate the volume from the length of the calibrated tube. In such cases its tilt must remain unchanged.

To preserve the sensitivity of the apparatus, it is advisable to fill the whole tube with water for a short time before it is reused, otherwise water vapours that condense inside it will interfere with the movement of the water.

Shirshov (1952) constructed an apparatus for measuring small root volumes. His volumeter consists of a cylinder (a tube with an inner diameter of 5 to 10 mm) that has a small funnel at the top end and a drain stopcock at the bottom. A knee is welded on at the lower part of the cylinder with a vertical capillary tube rising up from it; the tube is graduated in 100 0.01-cu cm divisions, i.e. the inner volume of the tube is 1 cu cm. A rubber tube, with or without a bulb, is fitted to the upper end of the capillary tube. To determine the volumes more accurately (by visualizing the levels) Shirshov used a third tube of the same height as the cylinder. With this apparatus he determined the volume of azotobacter nodules.

Shirshov's apparatus is operated as follows. The cylinder is filled with water to the mark engraved on it and the roots are lowered into the cylinder, as a result of which the water rises above the initial mark. After this the water is pumped off from the cylinder with the aid of the rubber tube until it falls again to the initial mark and is on a level with the water in the graduated tube (before the roots are submerged). After the water is pumped off from the cylinder the water level in the capillary tube will rise. The volume of the roots placed into the cylinder is determined from the difference between the water levels in the capillary tube. The roots are removed through the drain stopcock.

The volumeters, the tubes in particular, must first be degreased (washed with potassium bichromate or other agents). One should thoroughly check the sensitivity of the tubes and the uniform flow of water in them.

Shalyt (1949) determined the root volume on fresh material. To restore their volume, dry roots are placed in water for one or two hours, then carefully squeezed and slightly dried with filtering paper. After this the roots are put into a measuring cylinder of such a volume that it will be completely filled with them. Another cylinder of the same size is filled with water up to the mark, and then part of this water is poured into the cylinder containing the roots, also to the mark. The volume of water left in the second cylinder will be equal to the volume of the roots. Any air bubbles that form in the water are eliminated by carefully stirring the roots with a glass rod.

Shalyt measured the surface area of a root system by washing it on two sieves. He prepared two or three microscope specimens and measured the diameters of 100 to 200 roots. It is convenient to arrange the larger roots (primarily the longer ones) recovered from the top sieve, on the slide in parallel groups of ten to fifteen roots, securing them to the slide at the ends and in the middle with paraffin or wax. The diameter of each root is measured at three points; 50 to 100 measurements must be made in each root fraction; 18 to 33 roots should be taken depending on the degree of uniformity of the fraction. A low-magnification microscope with an eyepiece-ruler is used. Cover glasses are not employed. All the values obtained are converted to microns. The presence or absence of root hairs is recorded.

The lateral surface of the roots is determined from the

root volume and average root diameter (regarding the root as a cylinder) from the formula:

$$S = \frac{4\ v}{d}$$

where: $v =$ volume of the root system;
$d =$ diameter of the roots.

The length of the root system is estimated (first in each fraction, then along the soil horizons and in the entire trench) after the volume and surface of the roots in each fraction are found. It is determined from the formula:

$$L = \frac{4\ v}{d^2}$$

When treating the material Shalyt selected an average sample of small roots 2 to 3 g in weight, studied it carefully with the aid of binoculars, and then introduced a correction for the whole weighed portion. Then he estimated the ratio of the active parts of the roots to the inactive parts per 1 g of the above-ground mass and per 1 cu cm of soil by weight, volume, surface area, and length of the roots. Thus, the root length is estimated from their volume and average diameter, and after measuring 2 or 3 g of roots these values are determined for the whole weighed portion. The technique of root volume determination is described below (see Adsorption Method).

Savvinov and Pankova (1942) claim that determination of root volume by the amount of water displaced is inaccurate and recommend that the total root surface and volume be estimated from the total root length and average diameters, using the conventional formulas of the lateral surface area and cylinder volume.

Soldatov (1955) employed a method based on the determination of the volume of water in films covering a wet root strand. He submerged the roots in a measuring flask filled with water to restore their volume. Then the roots were taken out, the drops of water remaining on them shaken off, and their volume determined again, but this time from the moisture film covering them after the first submersion in water. The difference between the volumes of the wet and dry roots was multiplied by a coefficient (74.1) derived empirically, and thus the value of the root surface was obtained.

In studying problems of the microtrophicity of trees Lobanov (1947) measured the root surface area as follows. He placed the root net between two glass plates, inserted the plates into an epidiascope, and obtained a ten-fold projection of the roots on paper. Then he measured the root lengths and diameters and calculated the root surface from them.

We believe that the Sabinin-Kolosov and the Shirshov volumeters are well suited for measuring the volume of root systems.

Adsorption Method

The surface of a root system can be determined by a method based on the adsorption of various dyes or methylene blue on the roots, proposed by Kny (1898) and Büsgen (1905). This method is extremely valuable as an auxiliary and, in some cases, as an independent procedure employed in investigating the intricate relationship between the plant and the environment. The adsorption method as applied to the investigation of fruit species was elaborated by E. Kolesnikov (1960) under the guidance of Kolosov. It has attracted the attention of many researchers.

Adsorption is carried out in methylene blue solution $C_{16}H_{18}N_3SCl \cdot 3H_2O$. The molecular weight of methylene blue is 373.68. Before it is weighed the dye is desiccated to constant weight at 95 to 100°C. To obtain a 0.0002 per cent solution, 0.0747 g of methylene blue was dissolved in a litre of water. Groups of three or four plants were studied at definite intervals. The volume of the root system was estimated and a methylene blue solution was poured into three beakers, its volume in each being ten times the volume of the roots. Then the roots were lowered for 90 seconds into each beaker in turn, stirring the solution and carefully shifting and turning the roots and again lowering them to the bottom of the beaker. When they were taken out and the solution allowed to drip off back into the beaker, they were placed on filtering paper. Before the roots were put into the next beaker they were cleaned of all the methylene blue solution but not allowed to dry completely.

The adsorption of methylene blue was measured by means of a Duboscq or a K-1 colorimeter. The adsorbing surface area determined by this method is somewhat oversta-

ted because during the second submersion a certain amount of the dye penetrates inside the root cells.

The results are calculated by the formula:

$$x = \frac{aHv}{l}$$

where x=amount of methylene blue in the solution after adsorption;

a=concentration of the standard solution (0.0747 mg methylene blue per 1 cu cm of solution);

H=height of the standard solution in the colorimeter;

l=height of the solution under test after adsorption;

v=volume of the solution used for adsorption.

As an illustration we give (Table 56) the results obtained in studies of methylene blue adsorption on the root system of apple seedlings (E. Kolesnikov, 1960).

Table 56

Adsorption of Methylene Blue on the Root System of Chinese Apple Seedlings

(Sept. 19, root volume 21.51 cu cm; volume of solution $21.5 \times 10 = 215$ cu cm)

Characteristics	Beaker		
	first	second	third
Height of standard solution in colorimeter (H)	20	29	20
Height of solution obtained after adsorption (l):			
measurements 1st	28.9	27.2	27.3
2nd	29.0	28.1	27.8
3rd	29.8	28.2	26.8
4th	28.8	27.7	27.0
5th	29.0	28.3	28.2
Mean	29.1	27.9	27.4
Amount of methylene blue, mg:			
in solution after adsorption (x)	11.02	11.50	11.72
adsorbed on roots	5.03	4.55	4.33
in volume of solution taken	16.05	16.05	16.05
Adsorbing surface area of roots (S), sq m	5.30	4.78	4.55
Total adsorbing surface area (P_{ad}), sq m	10.08		
Absorbing surface area (P_{ab}), sq m			4.55

From the formula given above we find

$$x = \frac{0.0747 \times 20 \times 215}{29.1} = \frac{321.11}{29.1} = 11.02 \text{ mg}.$$

Since 100 cu cm of the solution contained 7.47 mg of methylene blue, 215 cu cm contained 16.05 mg (concentration of the solution), i.e. 16.05 — 11.02=5.03 mg was adsorbed from the solution. Kolosov proved in his recent works that in monomolecular adsorption 1 mg of methylene blue covers 1.05 sq m of surface (the figure accepted previously was 1.1 sq m). Consequently, multiplying 5.03 by 1.05, we find that the adsorbing surface measured 5.25 sq m.

The amount of methylene blue absorbed in the other beakers is estimated in the same manner.

The total adsorbing surface area (P_{ad}) is determined from the first two submersions and in our case equals 10.08 sq m, while the absorbing surface area (P_{ab}), found from the third submersion, is 4.55 sq m.

After the root system is submerged twice (for 90 seconds each time) into a methylene blue solution, adsorptive saturation occurs both in the active and inactive portions of the root system, since the methylene blue taken up previously by the cells is adsorbed by this time.

Kolosov suggested that the root length (m) and diameter (mm) be determined from the following formulas:

$$\text{total root length } l_1 = \frac{P_{ad}^2}{4 K^2 \pi},$$

$$\text{average root diameter } d = \frac{4 Kv}{P_{ad}}.$$

The coefficient K is a new value in the formulas; it is found thus:

$$K = \frac{P_{ad}}{2 \sqrt{\pi vl}}$$

The plants are selected and tied in bunches so that the volume of their roots should be about one cu cm. Accurate measurements can be made using Shirshov's volumeter. It is advisable to determine the coefficient K with five replications. The volume of the selected plants is found, and the adsorbing surface area determined from methylene blue adsorption by the technique described above.

After P_{ad} is determined from the first two submersions, the length of all the roots in each bunch is measured. For this purpose Kolosov used a wet glass placed over a piece of graph paper. He cut off the above-ground portion of the plant and arranged the roots on the glass. The main and lateral roots were straightened out perpendicularly to each other along the lines on the graph paper, so that their length could be measured easily and quickly. The obtained values of the volume (v), total adsorbing surface area (P_{ad}), and length (l_1) of the roots were substituted into the formula and the coefficient K found. It takes twelve to sixteen hours to calculate the coefficient K for a single culture with five-fold replication.

In determining the coefficient K it would be more correct to take into account not only the length of the roots, but also that of the root hairs; then the root hairs would also be included in the values of l_1, d, and P_{ad} found.

The coefficient K can be determined in root studies at different phases of plant development.

The main characteristics of the root system are: volume, root length, average root diameter, adsorbing and absorbing surface areas, and the specific active absorbing surface area $\left(\frac{P_{ab}}{v}\right)$.

The specific active absorbing surface area varies with the species and the environmental conditions. Investigations made in 1958 showed that in sand cultures on Hellriegel's mixture it averaged 0.195 in Chinese apple seedlings, 0.176 in sour cherry, and 0.332 in apple kept on a mixture containing no phosphorus. The high value of the active absorbing surface points to the presence of fungal hyphae on the surface of the roots studied (Kolesnikov, 1960).

CHAPTER 11

OTHER METHODS

Method for Studying the Distribution of Absorbing Roots in the Soil

In studies undertaken for various purposes certain investigators (V. A. Kolesnikov, 1924; Frischenlager, 1935; Devyatov and Balabin, 1959; Otto, 1960, and others) recorded the number of root tips on a plant or per unit of soil volume. This was taken into account by Weller (1962), the author of the method discussed, who believed that the true picture of the distribution of the root system of fruit trees in different soils and with different management could be obtained from the distribution of only the absorbing portions of the roots. Record is made exclusively of the number of root tips per unit of soil and not of the length of the absorbing roots. It is done very easily by counting the tips on the roots of washed-out samples, and this takes much less time than the estimation of the length and particularly the surface area of the absorbing roots. In Weller's opinion the method gives a good idea of the spatial distribution of the absorbing roots, which play the decisive role in the uptake and assimilation of water and nutrients.

The samples are collected from ten spots around the trunk, chosen at intervals of one metre (Fig. 57), being removed in vertical steps of 10 cm with a simple auger to a depth of one metre. Each sample is 100 cu cm in volume. They are placed in separate paper bags and stored till the root tips have to be counted.

At the laboratory each sample is soaked in water and then poured into a sieve with 1-mm mesh on which the soil is washed off with a moderate jet of water. When the water becomes clean the contents of the sieve are placed into shallow bowls, where the roots are separated from coarse soil particles and any remaining roots of other plants, herbaceous in particular. The separation and subsequent coun-

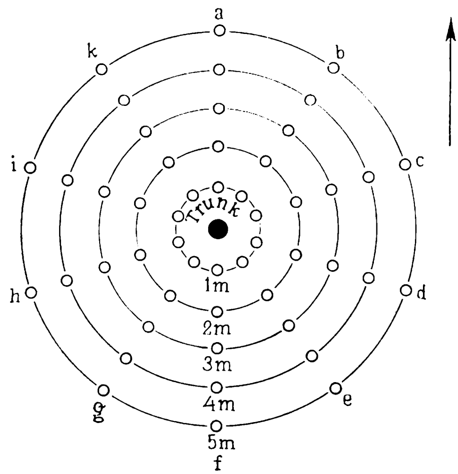


Fig. 57. Sampling technique suggested by Weller (circles indicate the sites for sampling)

ting of the root tips are done with the roots submerged in water because in this way they are easier to handle. Only root tips white to light-brown in colour and with a living primary cortex are counted, while those that are dark and especially those decaying are not recorded.

The results of counting the different samples taken from the same distances from the trunk are tabulated together (Table 57). On summing up ten parallels of every horizontal step the total number of root tips per unit volume of soil at the corresponding depth is obtained. It can be seen from the table that the difference from sample to sample may be great, even within the same depth; but with well aerated soils it is less marked than with poorly aerated waterlogged soils.

By using this method Weller obtained valuable information on the distribution of absorbing roots in the genetic horizons of different soils, and in relation to different techniques of soil treatment.

In our opinion, the method is undoubtedly valuable and should be employed. As was established by us earlier, the average length (root coefficient) both of the whole root system and of its parts in a fruit plant remains almost the same throughout the entire vegetative period, and because

of this the number of tips of the absorbing roots will give a correct idea of the dynamics of root growth in fruit trees or in any plants. For instance, in the case of fruiting apple trees with scion from Anis seedlings that have an average root length of 3.5 mm for the entire root system or any part of it, multiplication of this length by the number of root tips will show the dynamics of root growth expressed as the length of the absorbing roots and not only as the number of root tips.

Table 57

Record of Root Tips Found at a Depth up to Two Metres and at a Distance of Two Metres from the Trunk
(35-year-old Boskop apple tree on deep clay soil)

Depth, cm	Number of root tips in samples around trunk										Total
	a	b	c	d	e	f	g	h	i	j	
0-5	*D**	2	*D*	2	*D*	*D*	3	6	*D*	0	13
5-10	*D*	2	3	3	3	10	11	*D*	*D*	0	32
10-20	*D*	9	*D*	8	69	*D*	3	3	58	30	180
20-30	85	35	22	24	77	*D*	98	64	16	89	510
30-40	20	22	13	2	131	87	10	241	48	83	657
40-50	118	10	13	1	107	86	35	28	159	46	603
50-60	12	4	9	3	30	62	56	108	15	19	318
60-70	3	108	94	43	85	59	83	29	32	52	588
70-80	12	108	22	25	66	37	32	26	42	8	378
80-90	67	64	*D*	17	14	52	57	69	44	68	452
90-100	13	29	30	69	14	57	11	64	24	12	323
100-110	95	22	52	93	11	89	43	45	97	24	571
110-120	113	89	52	103	16	33	29	63	26	40	564
120-130	19	7	28	68	35	38	36	108	79	0	418
130-140	32	111	59	127	46	87	6	83	33	11	595
140-150	50	27	91	65	124	42	45	32	18	0	494
150-160	45	52	4	12	19	54	6	37	22	0	251
160-170	76	31	8	41	*D*	14	48	34	11	4	267
170-180	9	8	12	51	35	0	19	7	12	0	153
180-190	23	3	17	32	27	0	0	15	13	0	130
190-200	5	0	3	107	37	65	17	19	9	28	290

* *D*—Dead roots

Method for Studying the Root System on Slopes

Research into problems of highland fruit growing also involves studies of the root system of fruit species. The complicated character of the relief of slopes, the considerable variety of parent rock and soils, and the different tech-

niques employed for preparing the plots by terracing exert a considerable effect on the root system, its distribution in particular. Examination of the root system on slopes by methods used on flatlands yields inaccurate information resulting in discrepancies between conclusions made by different investigators.

Research carried out in Daghestan points to a number of special problems involved in a study of the root system on slopes (Kolesnikov, Kisriyev, Mursalov, 1967), namely:

(1) a study of the life-history of the trees, their age and planting methods (trenches, stands, artificial or natural terraces, ordinary pits without terracing, etc.);

(2) determination of the steepness and position of the slope, and the altitude of the locality (object under examination);

(3) establishing the nature of the soil surface, agrochemical and agrophysical properties of the soil, the degree of soil erodibility, the parent rocks.

The accuracy of experiments conducted on slopes depends not only on the correct choice of the plot and objects of study; definite rules of sampling and excavation must be followed. Thus, when taking samples for studying absorbing roots from different depths (monolith and free-monolith methods) or in trenches (profile, or trench method), excavations must be made strictly perpendicularly to the slope surface, otherwise, with sampling done at a slant the number of roots recorded will give the wrong idea of the distribution of the horizontal roots, including the absorbing ones, in the soil layers and at different depths. The steeper the slope, the deeper the horizontal roots will seem to be spread, the smaller their number per unit surface area estimated, and the thicker the humus horizon. For instance, with an incline of 30 degrees the depth of horizontal root penetration and the thickness of the root-inhabited layer will be increased and the density of the roots in the soil diminished.

A distinguishing feature of the root systems of trees growing on slopes is the pronounccdly irregular character of their spread both in the radial direction and downwards through the soil layers; this is apparently associated with the extremely varied conditions of the surrounding soil. That is why on slopes the whole root system of the tree must be excavated and not merely a quadrant or an octant, as is

admissible in studies of a root system on flatland (naturally, the tree dies following excavation of its whole root system). In exceptional cases with a simple slope relief half of the root system, including its parts lying highest and lowest on the slope, is excavated, or segments of one-sixth or one-eighth of the circle are unearthed. The idea of the root distribution in the soil and subsoil of the slope gained with this technique is very realistic, whereas excavation of half of the root system, highest or lowest on the slope, may lead to erroneous conclusions.

To study the character of horizontal root spread on slopes by the trench method it is advisable to dig the pits from three sides of the tree (upper side, lower side, and horizontally on a level with the root collar). Plans of the root tips seen on the trench wall, made to a definite scale (1:10), must show not only the distribution of the genetic soil horizons and the roots according to groups, but also the arrangement of large stones and rocks. Owing to such a comprehensive study of root distribution we were able to establish a fact of considerable importance to fruit growers working in highland areas, namely that without irrigation the vigour of roots lying along the lower side of a tree is two to two-and-a-half times that of roots on the higher side (Table 58).

Table 58

Number of Horizontal Roots in Relation to Their Distribution Along the Slope

Species	Number of horizontal roots		
	on side highest on the slope	on side lowest on the slope	total
Apricot	151	315	466
Almond	222	356	578

The sharply reduced amount of horizontal roots on the more elevated side of the tree can evidently be attributed to poorer conditions caused by the following factors.

1. The roots on the more elevated side of the tree lie not in the top horizon, which supplies the plant with nutrients, but much deeper because the trees are planted on stands or terraces that have recesses formed in their surface

when they are built, which are devoid of a top fertile soil horizon or a dam where the top humus horizon of the entire terrace bed accumulates.

2. The soil moisture is higher on the less elevated side because the surface waters that run down from the upper part of the slope are taken up by the soil surrounding the trunk and moisten considerably the lower segment forming the soil runoff. Pakhomova (1958), working on a terraced slope in Central Asia, also found the main mass of roots of almond seedlings under a water-retaining ditch and in the inter-terrace space, where most of the moisture accumulated after a rainfall.

The disturbed polarity between the roots located in the soil on the more elevated side and the above-ground portion apparently produces an unfavourable effect too.

The influence of the factors discussed in creases with the steepness of the slope. The different character of root spread

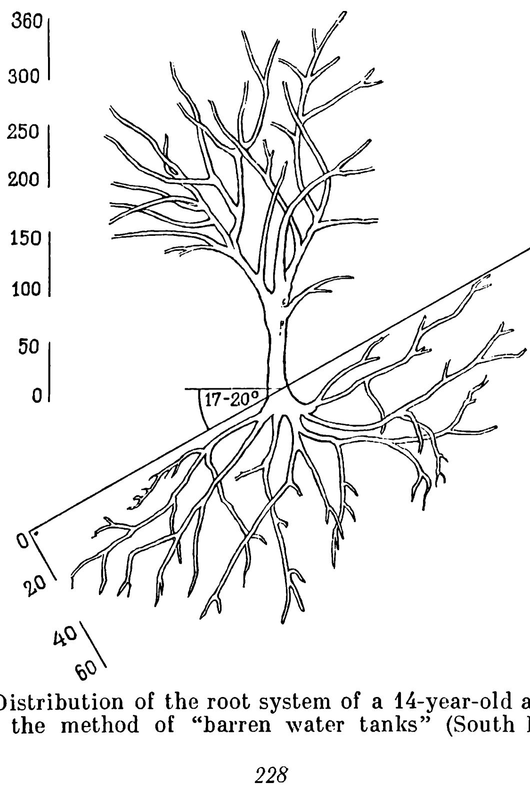


Fig. 58. Distribution of the root system of a 14-year-old apricot tree grown by the method of "barren water tanks" (South Daghestan)

is also associated with the biological peculiarities of the species and rootstock, or with the methods of tree planting. For instance, the specific root distribution mentioned above is less pronounced in relatively drought-resistant species than in moisture-loving ones. It must be added that trees planted on slopes without stands but with the use of stone mulch show a more or less regular distribution of horizontal roots (Fig. 58). This can be attributed not only to the copious accumulations of moisture in the soil through condensation of water vapours from the atmosphere, but also to the uniform distribution of precipitations over the entire area of soil surrounding the trunk.

Growing of Soil Cultures in Vegetation Vessels and Boxes

Specific features and purpose. Methods of growing water cultures in vegetation vessels were elaborated in different countries in the last century. They were described in special manuals and are widely used to this day to study nutrition in various plants, fruit plants included. The morphology, anatomy, physiology, and biochemistry of roots can be studied by growing plants in soil vessels and boxes filled with soil. In such cases the roots develop under conditions that are much closer to natural ones (orchard) than those provided for plants grown in vegetation vessels filled with water in which nutrient substances are dissolved.

Studies of root systems by growing plants in special vessels or boxes filled with ordinary soil or sand were carried out rather extensively as early as the second half of the nineteenth century. To facilitate the observations, some researchers inserted glass panels into one or several walls of the vessel.

Nobbe (1875) grew plants in boxes filled with alternate layers of fertile soil, sand, and unfertilized soil. The roots developed better in layers rich in nutrients. Heinrich (1876) studied the roots of plants grown in 4-m boxes containing soil. Orth (1892) grew plants in vessels with loose sand. Jamieson (1896) grew plants in vessels 75 cm high filled with soil, and determined the weight of the whole plant, of the roots, of the above-ground part, and the length of all the roots, the smallest ones included. King (1893) used vessels that could hold as much as 25 kg of soil. In studying

grasses Schulze (1908) dug pits up to 2 m deep and lowered special bottomless cages into them. One side of the cage had a sliding screen with a door through which root growth was observed. Miller (1916) employed metal vessels 60 cm high, that could hold 110 kg of soil, to study the influence of soil aridness on plant growth.

In 1907 Rotmistrov sowed herbaceous plants in narrow boxes 2.5 cm wide and 50, 75, or 150 cm in height and length. At the end of the vegetative period the boxes were pierced with rods to keep the roots in place and washed out with a jet of water. Chitrovo (1908) used boxes in which the soil was packed in genetic horizons.

Since 1915 Modestov widely used the method of growing plants in wooden boxes 1 m high. He packed the soil in layers differing in the amount of nutrients and established that fertile soils considerably influenced root development.

The containers used vary greatly in shape and material. There are large earthenware vessels for studying grape roots and cuttings, glass boxes, large boxes for studying apple roots under conditions of regrassing and bare fallow, quart glass pitchers for studying the effect of aeration on the growth of the root system of apple trees, tubs with one side fitted with a glass panel and a special latch for observation of root behaviour of fruit plants, narrow boxes fitted with two glass panels (spaced only 1 to 1.5 cm apart) for studying the root systems of dwarfing apple seedlings, and other types of containers.

Harris (1926) observed the effect of nutrients on the growth of the root system of plants employing observation boxes arranged in different ways in the soil.

Sideris (1932) watched the behaviour of pine-apple roots by means of sand-filled quadrangular boxes or flasks with different nutrients installed in the soil. In this manner he observed the activity of a single root and of whole groups of roots in different periods of plant growth.

Spivakosky (1962) successfully studied nutrition of apple trees by excavating the roots and placing them into a nutrient solution (in flasks) without separating the roots from the parent plant.

Some investigators installed the boxes at an angle of about 30 degrees to the direction of the usual root growth to facilitate root spread towards the glass.

There was a disparity among researchers as to the use of vessels, boxes, and other containers. Some, for example Kachinsky (1925), were opposed to the technique, claiming that the distribution of the soil in the containers does not correspond to the natural arrangement of the soil horizons. Others, Bystrikov (1934) among them, believed that the method made it possible to observe the whole root system, which is extremely difficult to do when the roots are excavated from the soil. According to Beideman (1938), when grown in containers "the root system of some plant species produces types and forms that are not determined by the soil conditions, but are inherent in the given species and only their secondary properties are altered by the conditions in the soil".

Method of soil box cultures. Priymak (1952) conducted special experiments to study the influence of various fertilizers on the growth and development of roots in fruit trees. To produce identical conditions within each variant all experiments were made on one and the same tree. Twofold experimental replications were made for each species. The boxes were filled with earth and fertilizers and buried in the soil in a trench 30 to 40 cm deep driven previously around the trunk at a distance of 1.5 m from it. Trial excavations showed that there was usually an adequate amount of fine skeletal roots at this distance and depth. Similar roots 1.5 mm thick were selected for all five variants. Such roots were usually encountered on different sides of the tree.

After the roots of the needed thickness were found, they were cut off at equal distances from the trunk and their ends were inserted into boxes of thin wooden planks filled with earth, which was taken from the site of root growth and mixed with fertilizers. The boxes were placed horizontally at the depth of root spread, and the trench was refilled with earth to ground level. The dimensions of the boxes ($30 \times 40 \times 50$ cm) ensured root growth. Soil management around the experimental trees throughout the entire vegetative period was the same as over the entire orchard area.

The experiments lasted from early spring to November, recording the reaction of the roots of apple, pear, sour cherry, apricot, and plum to the effect of fertilizers. In November the boxes were unearthed, and the main root was cut at the outer side of the box. All newly grown roots were carefully freed from the soil, taken out of the box, drawn

on a plan, and filmed. Then they were cut off the old root, separated into two fractions according to thickness— "thin" (less than 1 mm thick) and "thick" (thicker than 1 mm)—and their length was measured. Priimak obtained valuable information with this technique.

Method of soil vessel cultures. Kuznetsov (1956) of the Pomology Department of the Timiryazev Academy proposed dismountable metal vegetative vessels of special construction adapted for growing and studying the root system of fruit plant seedlings in field conditions. They make it possible to remove roots from the soil and wash them out at any time of the year. Their distinctive feature is the porosity of the walls and bottom, owing to which the regime in vessels placed in the soil is closely similar to that of the soil itself. For convenience the vessels are made narrow and dismountable (Fig. 59).

The body of the vessel is made of a porous sheet of galvanized tin 50×80 cm in size, rolled up into a cylinder. The edges of the sheet are joined together in several places with wire or special hooks, forming a vessel 25 cm in diameter. The bottom is made of a round piece of porous tin secured to the body with a wire.

The vessels, assembled and prepared for work, are filled with the required soil mixture and lowered into specially

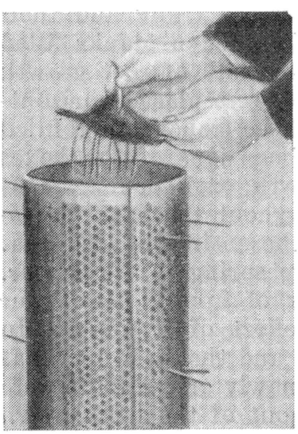


Fig. 59. Field vegetation vessel pierced with wire in two places (after Kuznetsov)

dug trenches, the size of which depends on the height, diameter, and number of the vessels. Then seeds are sown or the plants studied are planted, and the vessels are placed into the soil flush with the ground surface. Further care of the plants consists of watering, top-dressing, weeding, and hoeing of the soil in the vessels.

It is usually very difficult to study the natural distribution and growth of the root system in vessels because after being washed out of the soil and withdrawn from the vessels it usually loses its initial shape, gathers into a ball and becomes so entangled that it is difficult to straighten out. At the same time it is necessary to establish as accurately as possible the structure of the root system and the character of its spread in the vessel.

The author found that by inserting two metal nets with 5- to 7-mm mesh into the vessel, one in the middle and the other nearer to the top, the natural position of the root system could be retained after washing out. Progressive lignification of tissue in part of the root system also contributed to this.

Experience has shown that it is advisable to remove the plants from the vessels (after they have been taken out of the trenches) simultaneously and preferably with the use of a mild jet of water from a hose. To prevent the rootlet nets and individual roots from breaking during washing, metal rods are inserted through the sides of the vessel, slightly below or directly under the metal nets, so that the roots remain hanging almost in their natural position.

The vessel bottoms are separated before the roots are washed; this facilitates and speeds up the procedure, because the soil escapes with the water not only through the openings in the vessel walls but also through the bottom openings.

Method of semi-isolated nutrition in a soil culture is the name given to a modification of the technique described above, it was suggested by Kuznetsov (1956). He claimed that the techniques for testing soil mixtures and studying the roots' ability for selective nutrition and the structure and growth of the roots are very complicated, because they require many experimental variants. The necessity for replications increases the number of experiments still further.

Isolated nutrition of plants in water or sand cultures is widely used in agrochemical investigations. Kuznetsov

introduced considerable modifications into this method. Instead of two water-tight, usually glass, vessels one field vegetation vessel is used. It is divided into two or three compartments with sheets of plywood, and the compartments are filled with the soil mixtures studied to which fertilizers were previously added in different proportions and concentrations specified for the experiment. Then the plywood is taken out, so that the various soil mixtures come in contact. Care must be taken that they do not mix, and at the same time different conditions are provided in a single vessel for the growth of separate parts of the root system of one and the same plant. In this manner semi-isolated conditions of plant growth are created.

Kuznetsov established that due to its selective reaction to soil conditions the root system responded very sharply to any changes in them, showing marked alterations in its structure and distribution.

In our opinion, the vessels proposed by Kuznetsov are very convenient, while the method itself is quite promising. Another advantage is that the vessels are dismountable and do not require much storage space.

Method of soil pot cultures. To reveal the role of aeration when the contact between the soil and the root is disturbed, Noskova (1961) conducted two experiments for studying the effect of drainage on the growth and development of lemon seedlings, adding different amounts of sand to an optimal soil mixture of the second variant of experiment No. 1 (60 per cent clay+40 per cent sod earth+0.5 volume of humus).

The layout of the first experiment was as follows: (1) 100 per cent clay; (2) 60 per cent clay+40 per cent sod earth; (3) 20 per cent clay+80 per cent sod earth; (4) 100 per cent sod earth.

Layout of the second experiment: (1) 100 per cent soil mixture (control); (2) 95 per cent soil mixture+5 per cent sand; (3) 90 per cent soil mixture+10 per cent sand; (4) 85 per cent soil mixture+15 per cent sand; (5) 80 per cent soil mixture+20 per cent sand.

To evaluate the access of air to the roots when their contact with the soil was ensured, a third experimental layout was used with circular and central drainage for lemon seedlings grown in pots and trenches and with linear and central drainage for apple seedling soil cultures.

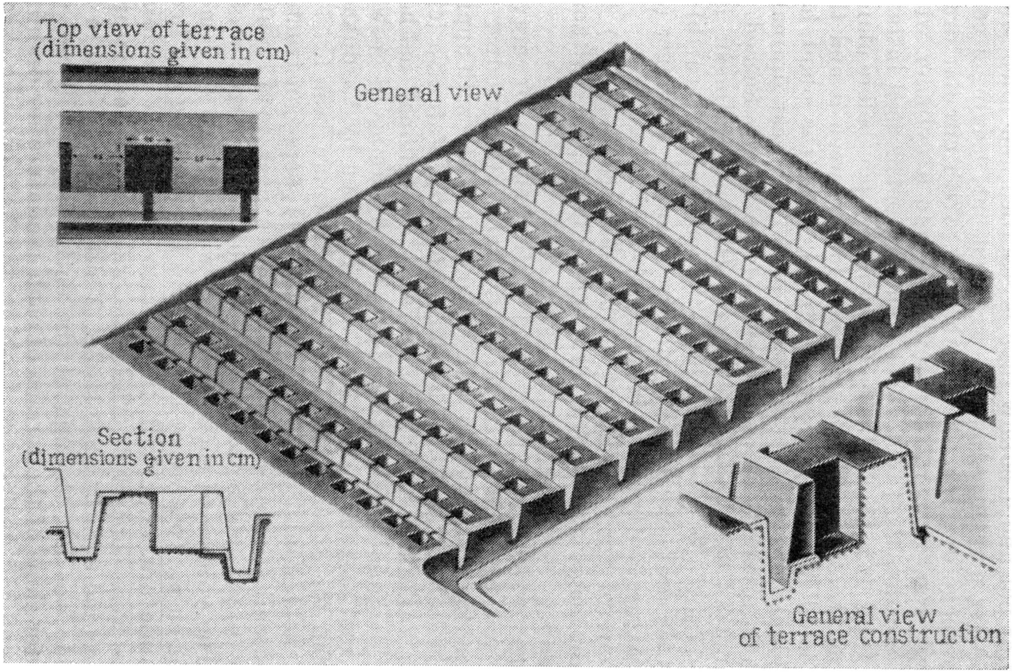


Fig. 60. Field miniature for studying root systems of subtropic cultures (after Patarava and Vardukadze)

The technique of setting up central drainage is very simple. Before planting, sand is spilled onto the bottom of the trench or pot and a hollow tube is installed and filled with sand. After planting, the tube is taken out, leaving a central drainage opening filled with sand. With circular drainage, plywood or cardboard rolled up into a cylinder with a diameter less than that of the trench or pot is used instead of the tube. It is placed inside the trench or pot before planting, and the space (6 to 8 cm wide) left between it and the walls is filled with drainage material; after the plant has been planted the plywood is removed. The linear drainage system is arranged along one side of the furrow formed.

Layout of the third experiment (lemon seedlings): (1) soil mixture (60 per cent clay+40 per cent sod earth)+ +circular drainage; (2) soil mixture+central drainage; (3) soil mixture without drainage (control).

Layout of the experiment with apple seedlings: (1) linear drainage; (2) central drainage; (3) control (without drainage).

Coarse washed-out river sand with pebbles or gravel added was used for drainage. Four plants were studied in the experimental variants with lemon and thirty with apple.

Method of cultures in soil field miniatures. Patarava (cited by Vardukadze, 1966) elaborated an original method of "field miniatures" for studying the dynamics of growth of the root system in plants. It was employed by Vardukadze (1966) for experimental work with Grecian laurel.

The field miniatures (Figs. 60 and 61) were constructed in Anaseuli (Georgian SSR) on terraces near to a water source (to provide better working conditions for root washing). The volume of each miniature was $0.6 \times 0.6 \times 0.7$ m= =0.252 cu m. To prevent the terraces from sliding and keep the miniature intact all the terrace slopes and draining ditches were concreted, while the walls of the miniatures were secured with bamboo sticks. A slit ("window") 10 to 15 cm wide was left throughout the entire height (70 cm) on the outer slope of the terrace of each miniature for draining water and soil during root washing and for removing excess precipitation during heavy rainfalls. Before the roots were washed out the slit was loosely covered with a board.

Carbonate and red virgin soils were removed from the top 35-cm layers for the experiment, thoroughly loosened, and freed from large stones. When the field miniatures we-

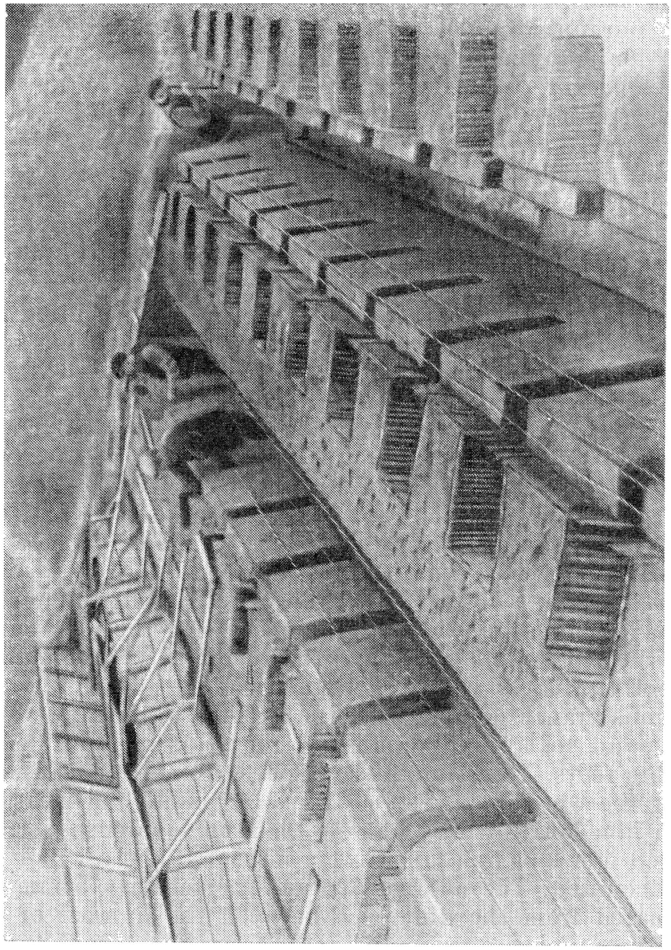


Fig. 61. Arrangement of terraces, general view (after Patarava and Vardukadze)

re packed mineral fertilizers were applied and laurel was sown. As the seedlings grew, their root system was studied in the first, second, and third year of life in the miniatures.

In our opinion, the method of field miniatures can be used for studying the root systems of fruit plants.

Method for determining the density of root branching. From studies of the root systems of apple, pear, plum, sour cherry, and walnut Frischenlager (1935) found that irregular distribution of water and nutrients in the soil greatly influences the formation of the root system. The best basis for comparison between the root systems of plants is a coefficient which expresses the root weight-to-number of root tips ratio. Its value ranges between 0.122 and 0.588. But this ratio is not exact because of root-shedding and loss of some of the lateral roots during washing. According to Frischenlager, the weight of the rootlets is negligible, whereas their length is considerable. That is why the root length-number of root tips coefficient is probably more correct.

Developing Frischenlager's idea, Otto (1962) came to the conclusion that the root length-to-number of root tips ratio better characterizes the density of fibre root branching, and suggested that it should be named Otto's coefficient. Thus, as a result of examining and counting the roots we have a fraction, the numerator showing the root length in a selected sample (mm), and the denominator, the number of root tips. Low values of Otto's coefficient will indicate vigorous branching and short fibre roots, while high values will point to a small number of root tips per unit length of fibre roots. To estimate the ratio, Otto collected samples along the whole root system of several plants and measured them in a Petri dish by placing them on squared paper. All roots 5 mm long and longer were measured and all root tips were counted. The number of roots shorter than 5 mm was estimated from the difference between the number of tips and the number of recorded roots 5 mm long and longer, while their total length was determined by multiplying the value obtained by 3 (3 mm was accepted as the approximate average length).

As an illustration Otto quoted the results of calculations of the root coefficient for nine clones of two-year-old apple seedlings; the experiments were done on eight plants with eight-fold replications. Fifteen root samples were collected

from each plant, i.e. 15 values of Otto's coefficient were obtained. The data were treated by variation analysis. The differences were mathematically authentic, which means that the coefficients obtained for each plant with the aid of the samples give reliable characteristics of the density of fibre root branching. The differences between the clones also proved to be quite reliable; this shows that the density of fibre root branching is largely determined by the genotype. Differences between the experimental variants due to varying soil conditions were also noted later, and though they could have been expected, the results obtained are of interest since the variants were confined to a relatively small area.

Similar results were obtained in another experiment involving apple seedlings planted in different plots. Marked differences between the plots were revealed after two months just by studying samples collected from each group of twelve seedlings.

The experiments show that Otto's coefficient reliably characterizes the density of fibre root branching and apparently confirm Frischenlager's opinion that the root length-to-number of root tips ratio is not a sufficiently accurate criterion and cannot be applied, for instance, to fruit trees. Thus, by estimating Otto's coefficient the researcher can determine whether factors of soil microbiology, the rhizosphere in particular, affect the density of fibre root branching along with such factors as the genotype of the plant and other soil conditions.

In addition, Otto's coefficient is evidently of interest to researchers in the field of plant- and fruit-growing. If there is a connection between the root length-to-number of root tips ratio and other criteria of productivity, particularly absorption of nutrients, then the estimation of the coefficient for only a small group of plants will help to reveal the optimal forms of the distribution of the root system in the soil. The question whether or not a plant is capable of intensive penetration (i.e. with a relatively large number of root tips) of the soil is apparently very important in the case of soils poorly supplying the plant with nutrients. The method can also be used for studying the growth of absorbing roots during the vegetative period and in the course of many years. It is evidently applicable to the root systems of older trees if it is conclusively established that

the samples obtained accidentally from the root system belong to the tree group studied. It is necessary to take into account considerable differences in the soil within the area occupied by large root systems and to have the required number of recorded samples.

Method for Separating the Absorbing Roots from the Fibre

The active roots effect absorption (mainly) of water and mineral salts and assimilation of organic substances. That is why it is important to separate them from the fibre and study biochemical processes occurring in them. The active roots can be seen distinctly on the washed fibres and readily separated with forceps, but a lot of time and work is needed to collect 0.5 to 1 g of them. Because of this we have elaborated the following simpler technique in cooperation with Schaufus (1962).

The root fibres are placed into a crystallizer or another vessel and carefully freed from the soil with a jet of water, which is then drained over the brim of the crystallizer. The washed roots are transferred to another crystallizer with clean water, in which they are thoroughly shaken so that the active roots break off the fibre and settle at the bottom. After this, the water is decanted, leaving only a little, and all the roots are shifted to one side of the bottom by slightly inclining the crystallizer. Then the roots are transferred with forceps into a small porcelain basin with water, cleared of soil and sand, shaken, allowed to settle, and transferred with forceps into another basin with water. The procedure is repeated two or three times until the roots are absolutely clean. After this, any remaining foreign matter (dead intermediate roots, etc.) is removed, using a dissecting needle and magnifying glass.

From half a gramme to one gramme of active roots must be obtained, depending on the purpose of the study. For our first analysis we collected 450 mg of active roots from about 40 g of roots (fibres), whereas the total length of the former accounted for only 35 per cent of the total length of the fibre. Therefore the method of separating active roots should be applied only if they form no less than 35 per cent of the whole root system, otherwise too many roots will have to

be cut off, which we believe will impair the vital activity of both the root system and the tree as a whole.

We have found that in the summer of 1959 the active roots of a 20-year-old apple tree contained 12.18 per cent of dry matter and 87.82 per cent of water, while the fibres without the active roots contained 29.38 and 70.62 per cent, respectively. That is why in studying a number of problems of the vital activity of fruit plants separate analyses should be made.

Method for Recording Root Hairs

The root hairs play an extremely important role in the life activity of fruit plants. They increase the absorbing surface of the root system, they take part in the absorption and assimilation of mineral substances and serve as the criterion of the degree of the plant's vital activity.

There are several techniques for recording the root hairs in some plants.

The Schwarz (1883) method. Root cross-sections are examined under the microscope and the number and length of the root hairs and the diameter and thickness of the cross-sections are recorded. Having determined the surface area, the number of root hairs per one square centimetre or millimetre is estimated. Muromtsev made as many as 25 measurements.

In studying the root system of cotton in Central Asia Tsivinsky (1933) distinguished active and inactive roots according to the condition of the root hairs. The vitality of the hairs was established by microscopic examination. Methylene blue and erythrosine in concentrations of 1:100,000 to 1:10,000 are usually used. Tsivinsky employed a 1:100,000 erythrosine solution, staining the roots for two hours; the living root hairs turned pale-red, while the dead roots did not take the stain. Seen through the microscope, the living hairs were of a whitish transparent colour with a fine darkish coating, while the dead hairs were brown, compressed, and sometimes coiled. In field studies the active rootlets were identified by the presence of root hairs on them, while the viability of the hairs was established from their colour under the microscope. The diameter of the active rootlets was determined from 25-35 measurements made on one root by means of an ocular micrometer.

The Dittmer (1937) technique. While Pavlichenko (1937) employed his own soil block washing method in quantitative studies of the whole root system of some plants, Dittmer studied the quantitative distribution of the root systems and root hairs of winter rye and other plants in a definite tillable soil layer. The soil samples (three-fold replications) were collected in the field with a tubular auger 7.6 cm in diameter from a depth of 15.2 cm. The washed roots together with the root hairs were stored in 5 per cent formaldehyde solution and then counted and measured carefully according to groups with the aid of binoculars and a microscope with micrometric gauges. From the count and measurements of the three samples the average values characterizing the root system in the given volume of soil were determined.

The Evans method. Evans (1938) described in detail a method for recording root hairs and surface of roots in sugar cane similar to that used by Shalyt today. The roots are also selected and washed, the foreign matter is removed, and the diameter of 200 roots measured. The samples are usually first placed in alcohol and then in xylene and paraffin, after which microscopic sections 1/10 mm thick are prepared with a microtome. About 60 roots are taken from each class and three or four sections are prepared from every root. The surface area of the root hairs is determined and the value of the surface of the white roots capable of adsorption in each group is added. It was found that the length of root hairs in cane sugar was 160 to 320 microns, while the average diameter was 9 to 14 microns.

Evans determined living roots by the method of plasmolysis and dye absorption. Even in the youngest roots plasmolysis was adequate in some hairs and inadequate in others. In old roots only a few hairs were filled with air, i.e. they had clearly ceased to function.

Kolosov (1939) counted the number of root hairs under a microscope, measured the thickness of the section with a micrometer screw, and then estimated the number of hairs along the entire length of the root portion covered with them. The length and diameter of the hairs are also determined under a microscope. The average hair length is estimated from 25 measurements, and the diameter, from four or five measurements. The root surface is calculated from these two values.

The method of Savvinov and Pankova (1942) is very similar to that of Dittmer, though they differ essentially in certain details. Dittmer confines his studies only to three 688.3-cu cm soil samples removed from the tillable layer (15.2 cm), assuming that samples taken from the top soil layers yield reliable information on the underground development of plants in field conditions. On the basis of his own experience and the data supplied by other investigators Savvinov disagrees with Dittmer because the distribution of the root system varies considerably with the plant species, soil, climate, and other environmental conditions.

Other essential differences between the two methods include the technique of sampling, size of samples, number of replications, techniques of measurement and estimation of total root length, etc.

An extremely important and valuable innovation is Dittmer's method for recording the total number, average diameters, length, and surface area of root hairs in root systems of plants grown in field conditions. It will undoubtedly be widely employed by pedologists and specialists in plant ecology.

The Muromtsev (1948) method employs a moist chamber. Stratified seeds with roots about 11 mm long (at the onset of sprouting) are collected, rinsed, and placed in a Petri dish on a round piece of filtering paper placed on a thin layer of water-saturated sawdust. The rim of the dish is coated with vaseline. The dishes are covered with lids and placed in a dark cupboard at 16 to 18°C.

The root hairs of 10-day sprouts are examined. In clones that vegetate by propagation, absorbing roots forming in the moist chamber are studied. This is done by placing the lower part of a cutting into a stoppered glass vessel filled to 1/3 its height with water-saturated sawdust. Rootlets that grow on the top portion of the root or stem in the damp air are examined. Experiments have shown that root hairs growing in a damp chamber are practically identical to those forming in the soil. For example, a 10-day-old Sargent crab apple seedling grown in a moist chamber had root hairs 190 microns long. The same seedling was planted in soil in a box with a glass wall and the root hairs that grew here were measured again a month later (through the glass) and found to be of the same size—190 microns.

Muromtsev established later that the diameter of root hairs and their number per 1 sq mm of a root of primary structure differed considerably with the apple variety. In Anis seedlings the average length of a root hair was 170 microns, the average diameter 13 microns, and the average number per 1 sq mm, 300. A root hair can be practically regarded as a cylinder and its surface area can be calculated from the formula for the side surface of a cylinder. The side surface area of a single root hair in the given case was $13 \times 3.14 \times 170 = 6{,}800$ sq microns, while the surface area of all hairs per 1 sq mm of root was $6{,}800 \times 300 = 2{,}040{,}000$ sq microns, or 2 sq mm (to the nearest whole figure). Thus, 1 sq mm of root surface had a root-hair covering of 2 sq mm, i.e. the total absorbing area of the root and root hairs was three units.

Though the root hairs play an important part in the life of a plant, their role should not be overestimated, since many plants do not have them (Schwarz, 1883; Ivanov, 1953), while in others they do not grow under certain conditions (Muromtsev, 1948). They are found on fruiting apples in the first half of the summer and in the autumn, but mycorrhiza prevails in the second half of the summer (Kolesnikov, 1959).

Of all the methods described the most suitable is the technique of root hair examination suggested by Muromtsev, though two important points should be borne in mind: firstly, the plants were grown by him in a moist chamber, and, secondly, roots of different branching orders were collected, and therefore the length and density of the root hairs were reduced. This is confirmed by the following data. The length of apple root hairs usually determined in field conditions is less than that determined by Muromtsev's method. The average length of root hairs in Sivers apple was 81.6 microns, while the maximal length was 163.6 microns (Dragavtsev, 1938); according to Rogers (1939), it was 25 to 50 microns, while in trees growing on clay soil it rarely exceeded 75 microns. Dittmer (1937), working in the state of Iowa (USA), found that the length of root hairs of winter rye decreased along the length of different branching orders from 1,000 to 860, 800, and 700 microns; their number per unit root surface (density) also decreased.

In conclusion we will point out that the nature and onset of root hair growth and the main conditions influencing it are still not clear and should be studied further.

Methods for Determining Root Diameter

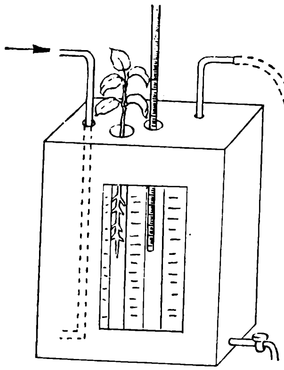
McDougal suggested that not only an increase in the trunk diameter but also an increase in the root diameter be recorded. For this purpose he excavated a skeletal root 1.5 and 14 m from the trunk and attached a dendrometer with a self-recorder to it. The dendrometer stood on a special support, which excluded any possible fluctuations. Such recording of the increase in the root and trunk thicknesses is of practical interest.

The root diameter is usually measured with a slide gauge or micrometer, but for measuring the thinner roots use is made of a microscope or binoculars with an eye-piece micrometer gauge. Shalyt (1949) advised that in the case of the finest roots the diameter of 100 to 200 of the roots should be measured under the microscope, the thicker and longer roots should be measured by placing 10 to 15 roots parallel on a slide, attaching them at the ends and in the middle with paraffin. Each root must be measured in two or three places. In Shalyt's opinion more reliable results are obtained if all the procedures are done by a single experienced person.

Methods for Studying Root Regeneration

In the period between 1936 and 1938 Schitt of the Timiryazev Academy elaborated a method for studying root regeneration in boxes filled with various nutrient mixtures. The method was developed further by Schitt himself and by his pupils and followers.

A small circular trench 30 cm deep and with a radius of 1 to 1.5 m is dug around mature trees in the spring and autumn. From all the skeletal roots that passed radially across the trench, those of the same length were recorded on a plan, numbered, and cut nearer to the inner trench wall. The portions cut off were thrown away, while the remaining ends were inserted into small boxes with soil taken from the same horizon of the trench. Definite doses of fertilizers were added to the soil in each box, with the exception of the control box. The trenches with the boxes in them were then filled with earth. In the autumn the boxes were unearthed and the roots washed and recorded. The experiments helped to establish the effect of different fertilizers on the regeneration of the root system.



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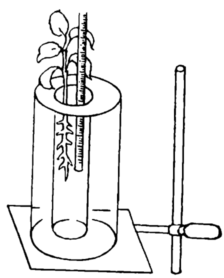

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Fig. 62. Two types of device for determining the effect of temperature on root growth (after Muromtsev)

Methods for Determining the Effect of Temperature on Root Growth (Muromtsev, 1955)

Type 1 device (Fig. 62) is used when the environmental temperature has to be either rapidly changed or maintained at a certain level for a long period of time. It is a closed rectangular vessel of 500-ml capacity. A thin (about 0.5 mm) glass, through which root growth is observed, is installed in its front wall with the aid of a water-tight putty. Two test tubes are fitted directly behind it: one for the growing plant root, and the other for a thermometer. Another glass is mounted in the back wall (opposite to the observation glass) through which a ray of light is directed from a lamp.

Besides, two metal tubes are fitted in the vessel. One of them—the receiving tube—extends to the bottom of the vessel, and water heated to the required temperature is poured into the vessel through it. Through the second—the drain tube—the water escapes from the vessel so that a continuous flow is maintained. The vessel is emptied through a tap at the bottom, which is closed during the experiment. The temperature is maintained at a constant level (to within $\pm 0.1\,^{\circ}$C) with the aid of an ultrathermostat.

Type 2 device (Fig. 62) is intended for prolonged observations with slower temperature changes. Here, both the root and the thermometer are in a thin-walled glass cylinder with a volume of about 55 ml. The cylinder is installed in a beaker against its wall. The temperature is raised, when necessary, with the aid of a spirit burner or a heating coil placed near to the bottom of the beaker. The temperature is recorded with a thermometer that has a long scale with divisions of $0.1\,^{\circ}$C.

The rate of growth is determined by direct observations through a horizontal microscope and by automatic filming. In the first case the end of a growing root is brought into the focus of the horizontal microscope that has an object-micrometer gauge fitted to the eye-piece, parallel to the root axis. The increase in root length is recorded at equal intervals (5 or 10 minutes), simultaneously recording the temperature. The data are entered in a journal.

To determine more precisely the rate of root growth over short intervals of time we constructed an automatic recording instrument. The image of the root, magnified by a horizontal microscope, is focused onto photographic paper wound on a cylinder which is rotated at one revolution per hour by means of a clockwork, moving the paper at the rate of 25 mm in five minutes. With the aid of the same clockwork the lamp of a flashlight is switched on for a short time every five minutes. Its light, concentrated by a short-focus objective, produces a time mark on the paper in the shape of a black dot. Pieces of thin wire are fitted to the slit aperture at intervals of 5 mm, and their projection produces a grid on the paper which helps to decipher the photogram. The initial focusing of the image and the control of the root position when the instrument is operating are effected by means of a revolving mirror which reflects the image of the root onto a frosted glass. The instrument indicates

changes in the rate of growth that occur over a period of two to two-and-a-half minutes.

Young seedlings of apple, sour cherry, plum, apricot, and peach grown from seeds were studied. They were cultivated on Merzhanyan's nutrient solution cr on tap water. Bean plants grown under similar conditions were used in some cases for the elaboration of techniques. The temperature and nutrition schedules for the period of plant growth (before the experiment) were assigned according to the purpose of studies.

Method for Photographic Sketching of the Root System

A camera is an excellent instrument for making photo sketches. Besides magnifying, it enables the researcher to make accurate sketches of the original object. Instead of photographic paper a sheet of drawing paper is placed on the magnifier screen on which the image of the negative is projected. The negative shows not only the contours of the object, but also their different shades, and the image thus produced is then sketched. The method is widely used by artists, and it was applied for studying the apple root system at the Pomology Department of the Timiryazev Academy (Pilshchikov, 1967).

Modern photography offers a great variety of techniques, but the important requirement is that the photo image must be simple, clear, convincing, and easily discernible.

With this method the investigator can represent on paper, to any scale, the pattern of the natural spread of the root system and determine the length, diameter, and depth of penetration of the roots in laboratory conditions at any time of the year. He can also obtain a clear idea of the root distribution according to the genetic soil horizons and to the various species, rootstocks, varieties, age, and agricultural measures. The use of the method saves time, particularly in expedition approbation of land. Besides, with the method of photo sketching it is possible to combine two procedures: making usual drawings (representations of the roots on a plan in field conditions) and taking photographs of the exposed and freed roots. A knowledge of the specific features of root distribution according to the soil horizons and of the condition of the roots allows the researcher to reveal changes undergone by the roots with the depth of

the soil profile, while the root patterns in each horizon show him whether the conditions there are favourable for root activity and allow him to recommend a series of necessary agricultural measures.

In taking photos, the axis of the camera should be strictly perpendicular to the object. Large objects should be photographed in several stages. Before a photo is taken it is advisable to paint white all dark-coloured roots and to measure the diameter of two to four roots or to place a measuring rule so that the appropriate scale can be chosen when the image is projected from the film onto the paper for sketching. This ensures an accurate picture and saves much time. A photo enlarger, epidiascope, or a children's film viewing apparatus can be used as the projector.

The method of photo sketching makes it possible to obtain final documentary and illustrative material to any scale; it greatly facilitates the drawing of the roots and obviates the need of making a root plan in field conditions.

ASPECTS OF FRUIT PLANT ROOT SYSTEM STUDIES

Information gained from studies of the root system provides a basis for the introduction and improvement of such measures as: (a) appraisal of new lands for orchards; (b) preparation of the soil before planting, and arrangement of the different species and varieties in the orchard; (c) time and depth of soil cultivation, application of fertilizers, and irrigation; (d) ensuring stable and high annual yields in fruit orchards.

We believe that studies of the root system of fruit plants must cover the following urgent problems.

1. Investigation of the root systems of fruit plants in all fruit growing zones of the country, including the study of the specific features of growth, development, and distribution of the root system in different soils and subsoils, among them the root systems of trees with record yields, weakened trees, trees with dried-up crowns, and trees damaged by agricultural implements (healing and regeneration of roots).

2. Study of the growth waves (rhythm) of active roots in the existing orchards in relation to the species, variety, rootstock, soil, climate, age, yield capacity, state of fo-

liage, state of individual elements, and the entire set of cultural measures.

3. Study of the root hairs and revealing species whose roots have mycorrhiza; study of the relationship between the mycorrhiza and other microorganisms (in the rhizosphere) and the active roots.

The above-ground part of the plant, the soil complex, and the cultural measures should be studied simultaneously. It was stressed by Keller (1935) that the plants are most intimately connected with the ever-moving, ever-changing external environment, which is constantly mutually affected by the plants.

It is also important to start or continue the investigation of the following problems : the biochemical features of the root system; new growth and dying off processes in the root system; the correlation between the assimilating surface of the leaves and that of the absorbing roots; the mutual effect of the root systems of homogeneous and heterogeneous plantings in orchards; the interrelationship between the vital activity of absorbing roots in the autumn-winter period, lignification of shoots, and the resistance of plants to frosts and to desiccation of branches and shoots in the winter period; the development of the root system of fruit plants in relation to the previous soil cultivation; the effect of pruning of the above-ground part and the root system on root regeneration; the effect of growth stimulators on root formation and regeneration, etc.

We give here a slightly modified programme for studies of the active part of the root system in fruit and berry plants suggested by Muromtsev (1967).

1. *Evaluation of the activity of the root system in statics (at the moment of study) and in dynamics (during the year).* Thorough investigation along these lines will not only bring us nearer to a knowledge of the general laws governing the development of the root system, which is important in practice, but also will ensure a relatively quick appraisal of the influence of environmental factors. The results of the studies must form the basis for a rational system of root care, particularly for the appropriate nutrition schedule. The main objective of these investigations is to establish the degree of development of the absorbing roots relative to the whole root system. It is convenient to express this activity by the ratio of the total absorbing

root length to that of the parent root. In some cases, especially in joint examination of root hairs, the ratio between the surface areas of the absorbing and conducting roots will be a reliable criterion. It is also important to take into account the state of the conducting roots themselves; for example, the prevalence of the suberized portion often points to unfavourable conditions for root growth.

2. *Anatomy of the root system of fruit plants.* Studies of the anatomy of absorbing roots aid in establishing the dependence between the structure of the root and its main functions, yield information on the life span of individual parts of an absorbing root and on its reorganization when it changes to the secondary structure, and help to reveal the influence of particular factors on the absorbing roots. Investigations in this direction are conducted on a limited scale as yet, but their importance is obvious.

Extremely valuable information can be obtained by using fluorescent microscopy and fluorescent dyes. Attention must be given to detailed investigation of the changes occurring in the anatomical structure of an absorbing root with age, and the type of reorganization taking place when the root changes from primary to secondary structure, taking into account the prevalence of two types in fruit plants, synchronous and asynchronous. The type of reorganization largely determines a number of essential biological features of a root system and is closely associated with the biology of the plant as a whole.

Special attention should be paid to the study of the root hairs, primarily to the determination of their length and number per unit absorbing root surface area. As a first approximation, root hair studies can be made in field conditions, but more detailed data can be obtained by laboratory techniques such as the glass wall method.

3. *Study of the effect of environmental factors on the growth and condition of absorbing roots.* It is difficult to overestimate the significance of this aspect of research into the root system of fruit plants, although no due attention is given to it so far. The studies should include, in the first place, the most important factors that determine the growth and physiological state of the roots, i.e. the environmental temperature (with determination of the cardinal points—minimum, optimum, and maximum, and damaging temperatures, both low and high) and moisture content (in-

cluding studies of the influence of arid conditions and excessive moisture). An extremely important factor, which receives little attention, is the relative air humidity. It rapidly affects root growth via the foliage activity and in some cases obscures the influence of other factors.

This aspect of research is extremely complicated and the choice of techniques is solely determined by the concrete purpose of the experiment. An important, though not always easily attainable objective is that one should strive to maintain all factors (except the one under test) at the maximally constant level throughout the experiment. This does not mean, however, that the stabilization of all environmental factors is a necessary condition. Thus, in most experiments the natural change from darkness to light (night and day) is evidently more desirable than continuous light.

4. *Study of the absorptive activity of the root system in fruit plants.* The problem can be divided into two close but not identical parts: (a) the absorption of water, (b) the absorption of substances dissolved in the water.

Firstly, it is of interest to determine the extent of changes in the absorptive power of an individual absorbing root with age, i.e. with the development phases. Secondly, in future studies attention must be paid to the special features of absorptive activity of roots in different varieties. Finally, it is necessary to widen research into the influence of the most essential environmental factors on the main root function, i.e. the absorption of water and dissolved substances. This work should be closely correlated with investigations in the field of the functional anatomy of plants.

All that was said in the preceding item with regard to the techniques refers to the present item as well. Methods employing labelled atoms and fluorescent dyes must play an important part in the investigations. As research advances, attention should be paid to the study of the fine mechanisms of absorption, including the study of intracellular structures and problems of absorption energy.

It is especially important not to disregard the correlation between foliage activity and root activity in these studies.

5. *The elaboration of a unified programme of observations of root growth and root activity in fruit plants.* The present knowledge of the root system and the availability

of a number of tested methods brings to the forefront the problem of working out a unified programme of the study of fruit plant root systems. Apparently, two programmes should be prepared at the beginning, one dealing with the most important and simplest (for recording) information (phenological phases of root growth, determination of the activity of the root system; it is advisable to conduct such studies at variety-testing plots), and the second, more detailed, should cover studies in root observation laboratories. The second programme can be recommended for those variety-testing stations or research institutions where the approriate conditions can be provided.

Studies conducted according to these programmes will aid in forecasting a number of phenomena such as copious early leaf shedding, which is fraught with severe consequences for fruit growing, and other events in the vital activity of fruit plants.

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